# *"Burning the Trash"*

## *Recycling Americium-241 in a Boiling Water Reactor*

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*University of Tennessee*
*Department of Nuclear Engineering*

*ORNL Student Seminar Series*
*26 June 2008*

# Outline of Presentation

- The Cast
- The Problem
- Recycling Americium in a BWR
  - Lattice Optimization
  - Core-Wide Analysis
  - Future Endeavors

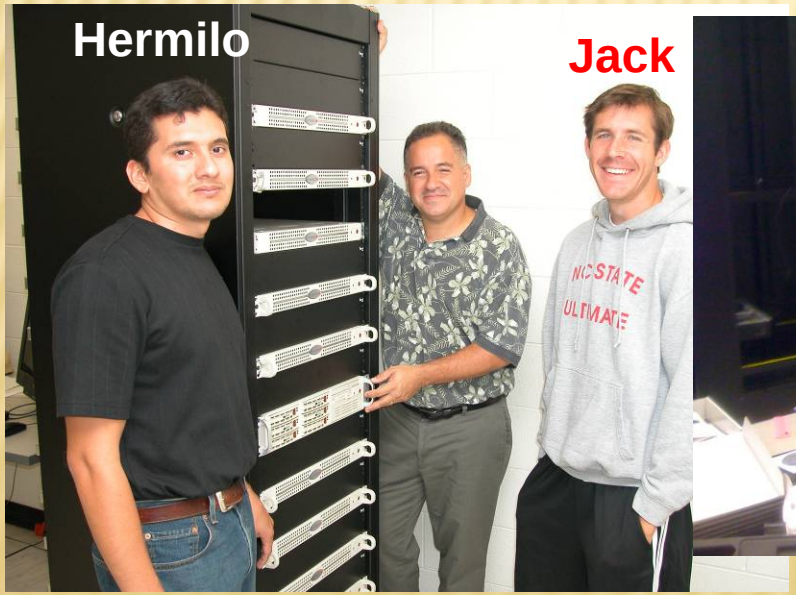
# En Route to Rocky Top

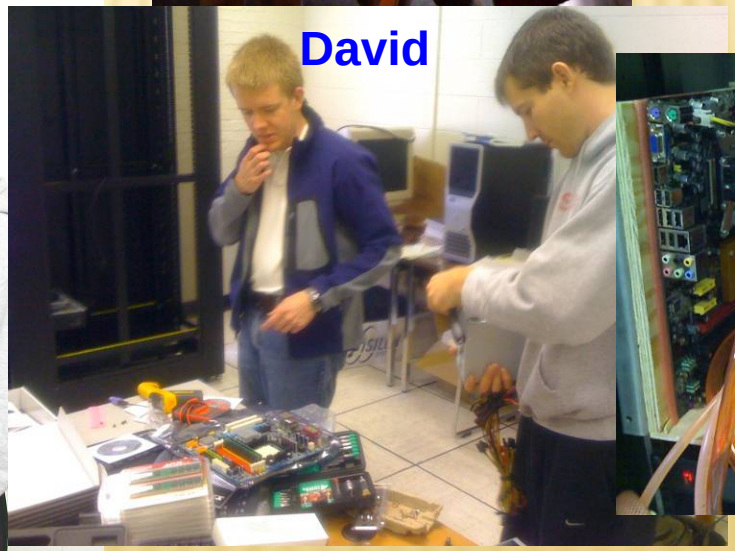
- One-way ticket: Ecuador to West Unity, OH (1979)
- OH/NY/NC National Guard (1980-89)
- University of Toledo, BS Engineering Physics (1985)
- GE KAPL (Naval Reactors) 1985-87
- MS & Ph.D. Nuclear Engineering, NC State (1987-93)
- Visiting Researcher, Electricité de France (1993-94)
- Asst. Prof. Iowa State Univ. (1994-99)
- Tech. Prog. Mgr, GE Nuclear Energy / GNF (1999-03)
- Assoc. Prof., Univ. of Cincinnati (2003-2007)
- Assoc. Prof., University of Tennessee (2007)
- Joint Faculty Appointment with ORNL (2007)

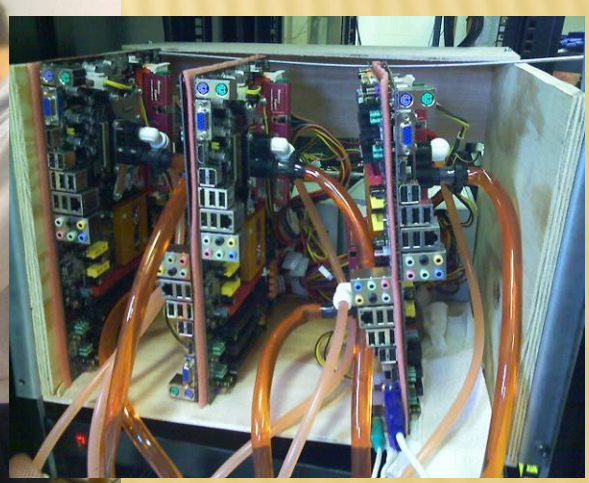
# Combinatorial Optimization Problem…

# My Family

# Go “Big Orange”!



# Jack Galloway

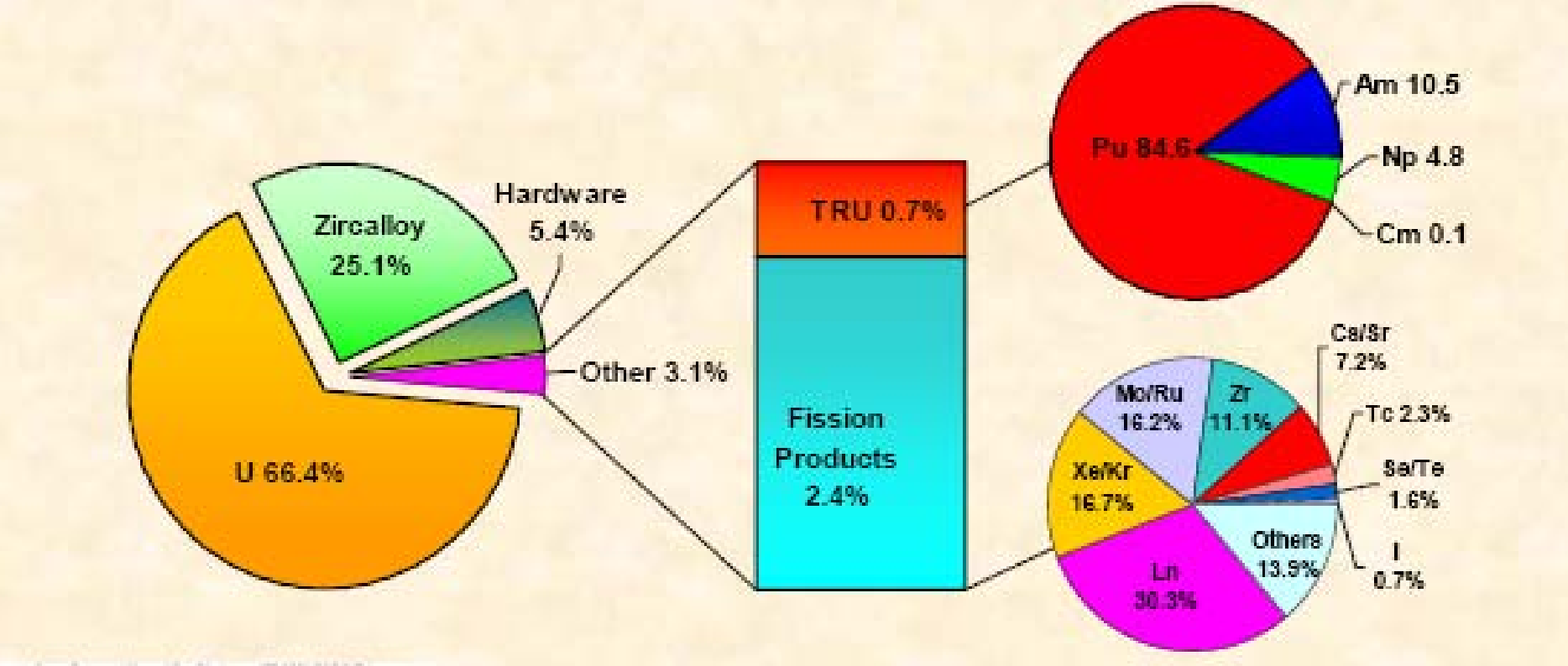
- BS in nuclear engineering from NC State University in 2004.
- Intern with GE/GNF in Wilmington, NC (2002, 2004).
- Joined Prof. Maldonado at the University of Cincinnati in 2005.
- National Science Foundation STEP teaching fellowship (2006).
- MS in nuclear engineering at UC in 2006.
- NESLS intern at ORNL with at the SNS in 2007.
- SCALE Training Course in 2007.
- Joined Prof. Maldonado at University of Tennessee in 2007.
- Currently at ORNL sponsored by NSTD reactor analysis group
- Pursuing Ph.D. degree in nuclear engineering at the UT.

# Hermilo Hernandez

- Obtained BS in Electrical and Electronic Engineering from the National Autonomous University of Mexico (UNAM) in 2003
- MS in Energy Engineering from UNAM in 2005.
- Received the “Best Bachelor Thesis in Nuclear Science and Technology” award from the Mexican Nuclear Society (SNM).
- Joined Prof. Maldonado at UC in 2005.
- Obtained the MS degree in nuclear engineering at UC (2006).
- Joined Prof. Maldonado at UT in 2007.
- SCALE Training Course in 2007.
- Currently at ORNL sponsored by NSTD reactor analysis group.
- Pursuing Ph.D. degree in nuclear engineering at the UT

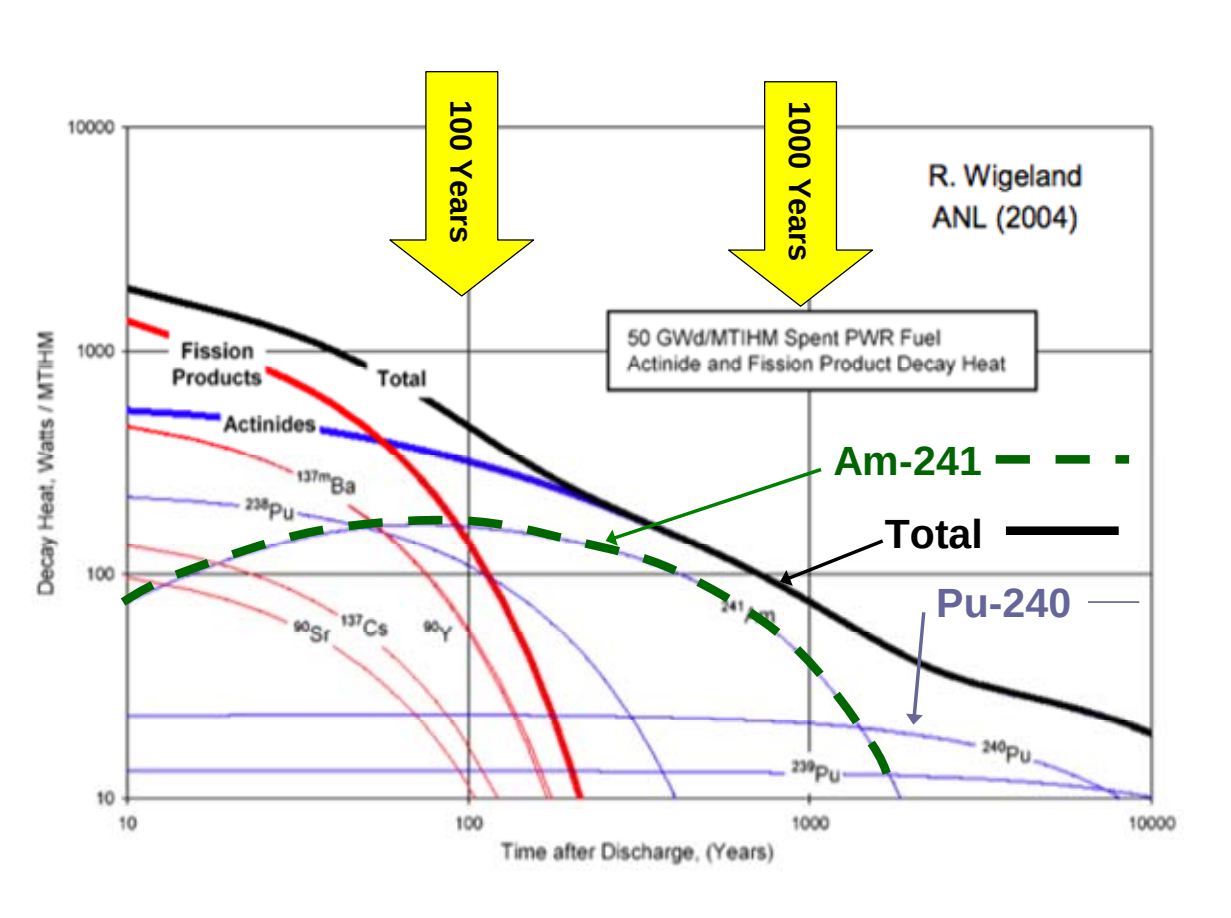
# US LWR Nuclear Waste

- More than 55,000 MT of heavy metal in spent fuel has been accumulated (legacy fuel)
- We continue to produce ~2200 MT/year
- Current projected capacity of Yucca Mountain
- NWPA limits the capacity of the proposed Yucca Mountain repository to 63,000 MT



# The Problem: Actinides in LWR Nuclear Waste

Note decay heat contribution from actinides, especially from Am-241 between 100 and 1000 years post-discharge.



# Possible Solutions

- Transmute with accelerator-driven systems
- Transmute actinides in fast reactors
- Drawbacks:
  - These systems don't currently exist in the US
  - They cost a lot of money
  - May take a LONG time to develop, test, and operate
- Possible Alternative:
  - Use less efficient approach to transmute in <u>thermal reactors</u>
  - 104 safe and operational LWR's potentially available!

# Background on LWR Recycling

- Considerable experience exists in the recycle of plutonium in LWRs (Europe and Japan).
- US recycle of weapons-grade material in LWRs as MOX fuel is planned.
- MOX LTAs loaded in the Duke Power Catawba reactor.
- Use of MOX fuel for burning plutonium has been demonstrated.

The introduction of other actinides such as Np, Am, and Cm, into LWR fuel has not yet been established and presents several challenges

- Manufacturing (volatility, chemical form, etc).
- Handling, and Transportation
- Potential impacts upon reactor performance.

# Manufacturing Options

- G. D. Del Cul, et.al., ORNL/TM-2005/108 "Fuel Fabrication Development for the Surrogate Sphere-Pac Rodlet,"July 2005.

**Table 3. Estimated compositions of sphere-pac pins**

| Sphere composition | | Uranium enrichment (wt %) | Americium (wt %) | Mass (g) | | | | Irradiation time (years) |
|---|---|---|---|---|---|---|---|---|
| Coarse | Fine | | | $UO_2$ | $AmO_2$ | $ZrO_2$ | Zr | |
| $ZrO_2$ | $ZrO_2$ and $AmO_2$ | -- | 10 | -- | 3.1 | 24.5 | -- | 2 |
| $UO_2$ | $UO_2$ and $AmO_2$ | 5 | 5 | 48.2 | 2.9 | -- | -- | 1 |
| $UO_2$ | $UO_2$ and $AmO_2$ | 5 | 10 | 45.4 | 5.8 | -- | -- | 1 |
| $UO_2$ | Zr and $AmO_2$ | 5 | 10 | 39.6 | 5.5 | -- | 3.6 | 2 |

# DOE NERI Project (2005-2008)

- US DOE NERI proposal developed by University of Cincinnati in collaboration with ORNL, LANL, and Westinghouse (2004).
- Proposal awarded in 2005: "BWR Assembly Optimization for Minor Actinide Recycling" (2005-2008)
- Westinghouse and UC signed software license agreement (SLA) for PHOENIX, POLCA, and the CoreMaster2 core design work environment (2005).
- Software tools delivered and installed; PHOENIX (2005), CM2-POLCA (2006).
- SLA signed with NCSU EPRC to employ the FORMOSA-L lattice optimization code (2006).
- SLA amendment signed with Westinghouse with Exelon's concurrence to use Quad Cities 2 Optima-2 Equilibrium Cycle as test bed (2006).

# DOE NERI Project (2005-2008)

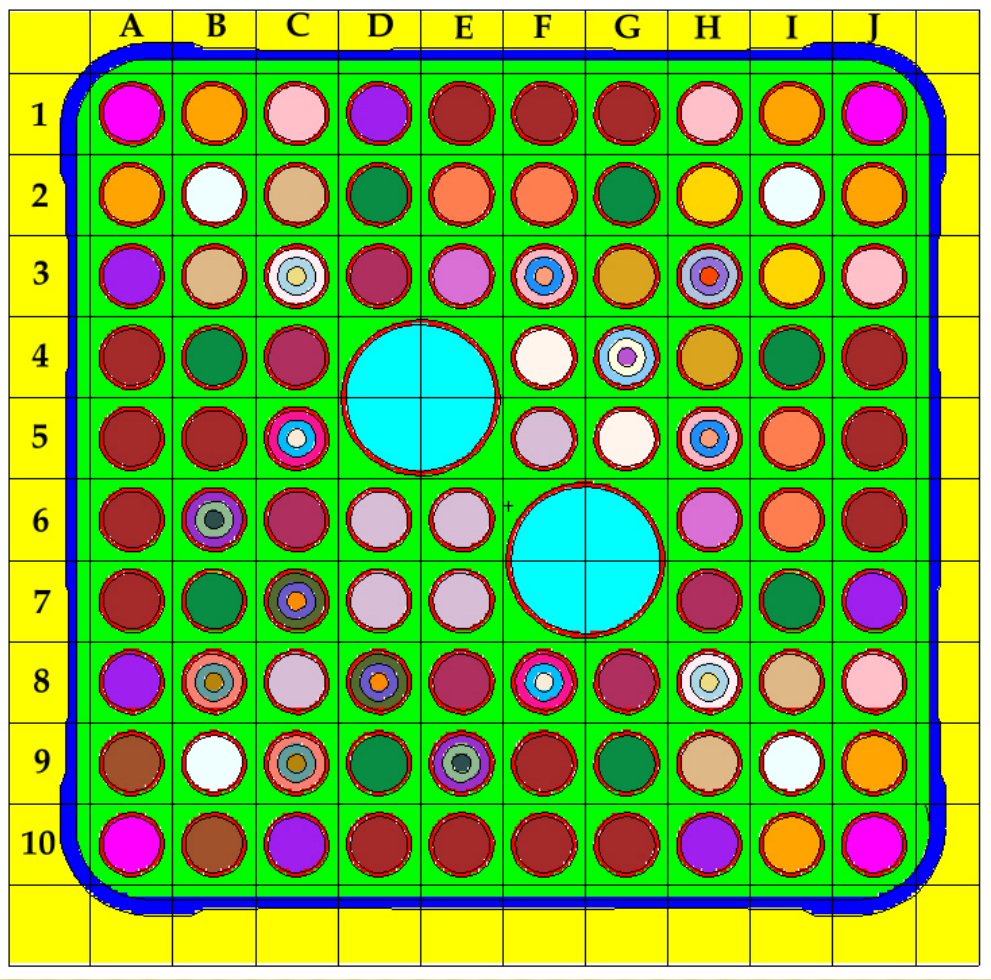
## Some Publications…

- M. Erighin, C. Yin, J. Galloway, G. I. Maldonado, "Analysis of BWR Lattices to Recycle Americium," PHYSOR-2006, ANS Topical Meeting on Reactor Physics Organized and hosted by the CNS, Vancouver, BC, Canada, D063, 1-10/10, Sept. 10-14, 2006.
- H. Hernandez and G.I. Maldonado, "Application of Simulated Annealing Optimization to Recycle Minor Actinides in a BWR Lattice," 2007 ANS Annual Meeting, Boston, MA, June 24-27, 2007.
- Jack D. Galloway and G. Ivan Maldonado. "Three-dimensional Core Simulations of BWR Bundles with Americium Target Pins," 2007 ANS International Meeting, November 11-15, Washington DC.
- J. Galloway, H. Hernandez, and G.I. Maldonado, "OPTIMIZATION OF AMERICIUM-LOADED LATTICES TESTED IN 3D BWR CORE-WIDE SIMULATIONS," PHYSOR 2008, Kursaal Conference Center, Interlaken, Switzerland, September 14–19, 2008.

# Tools…

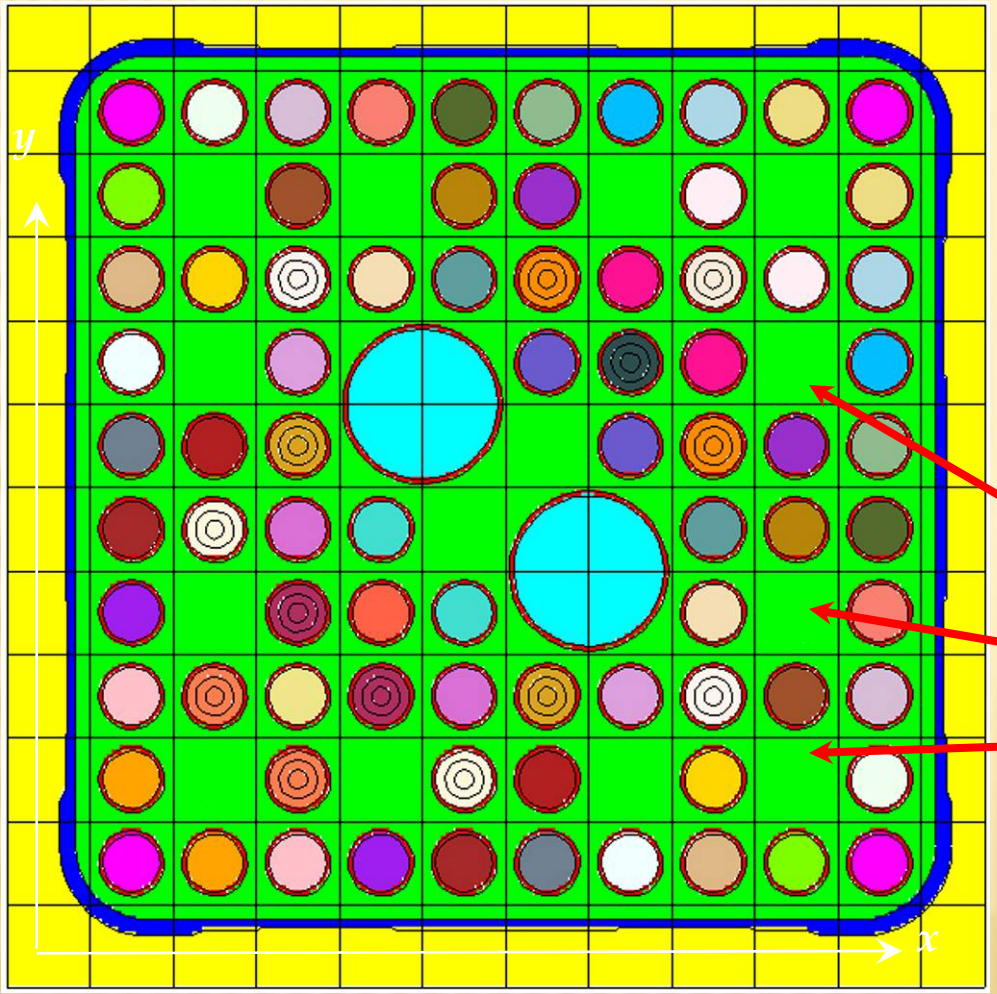
- Phoenix-4
  - Lattice physics
- Polca-7
  - 3D nodal core simulator
- CoreMaster2
  - GUI-based and user-friendly "work environment" that facilitates BWR core design by coupling lattice to core design
- MCNP5 & MONTEBURNS
  - Benchmarking, coupling of ORIGEN to MCNP5 for depletion.
- FORMOSA-L
  - Lattice loading optimization
  - CPM-2 employed to "jump start" this aspect of project

# Lattice Types (10x10 GE12) - Dominant




- Dominant Zone (lower axial region of bundle)
- Defined material regions for Monteburns depletion
- Employed concentric rings in gad pins

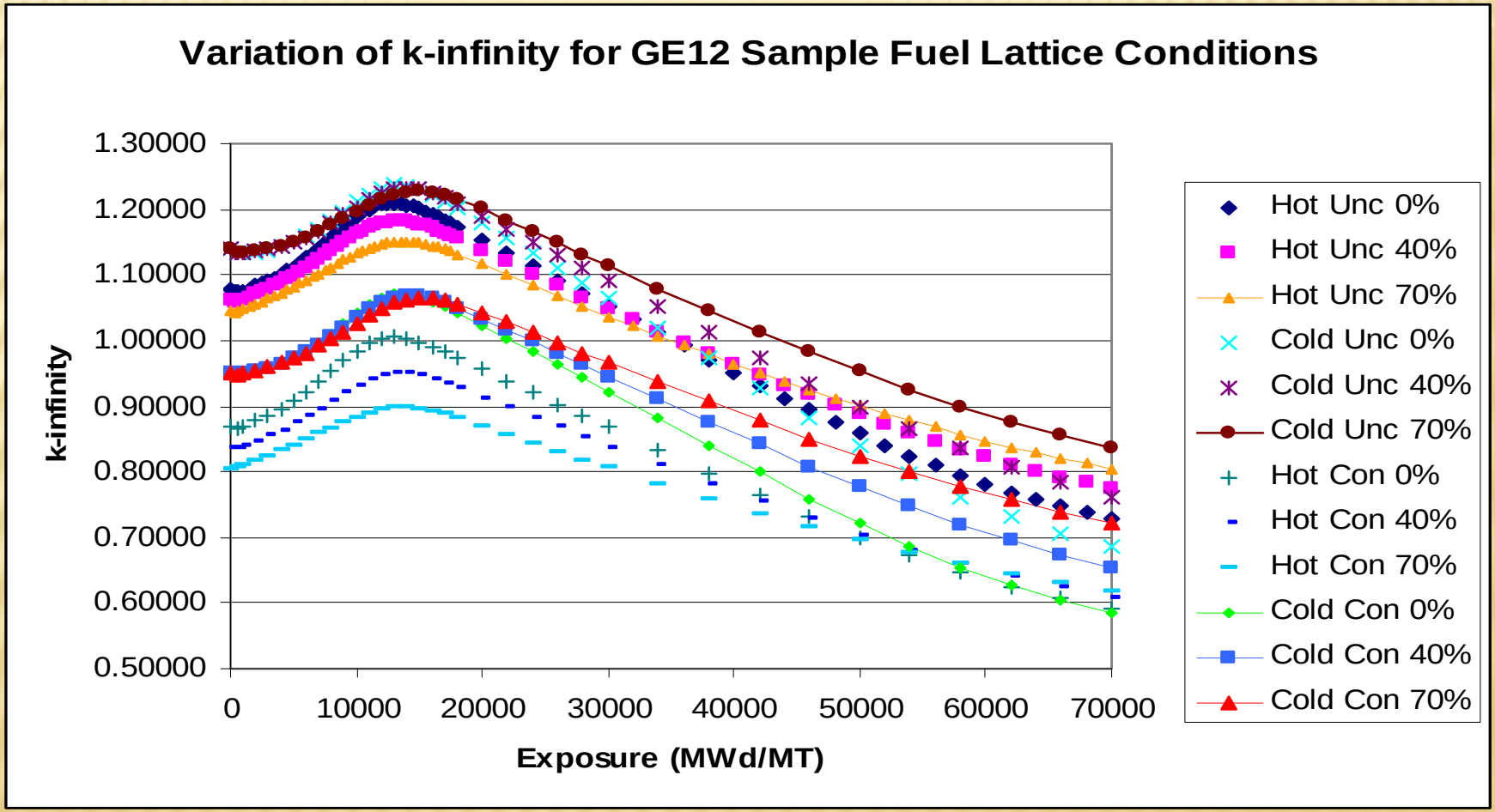
# Lattice Types (10x10 GE12) - Vanishing



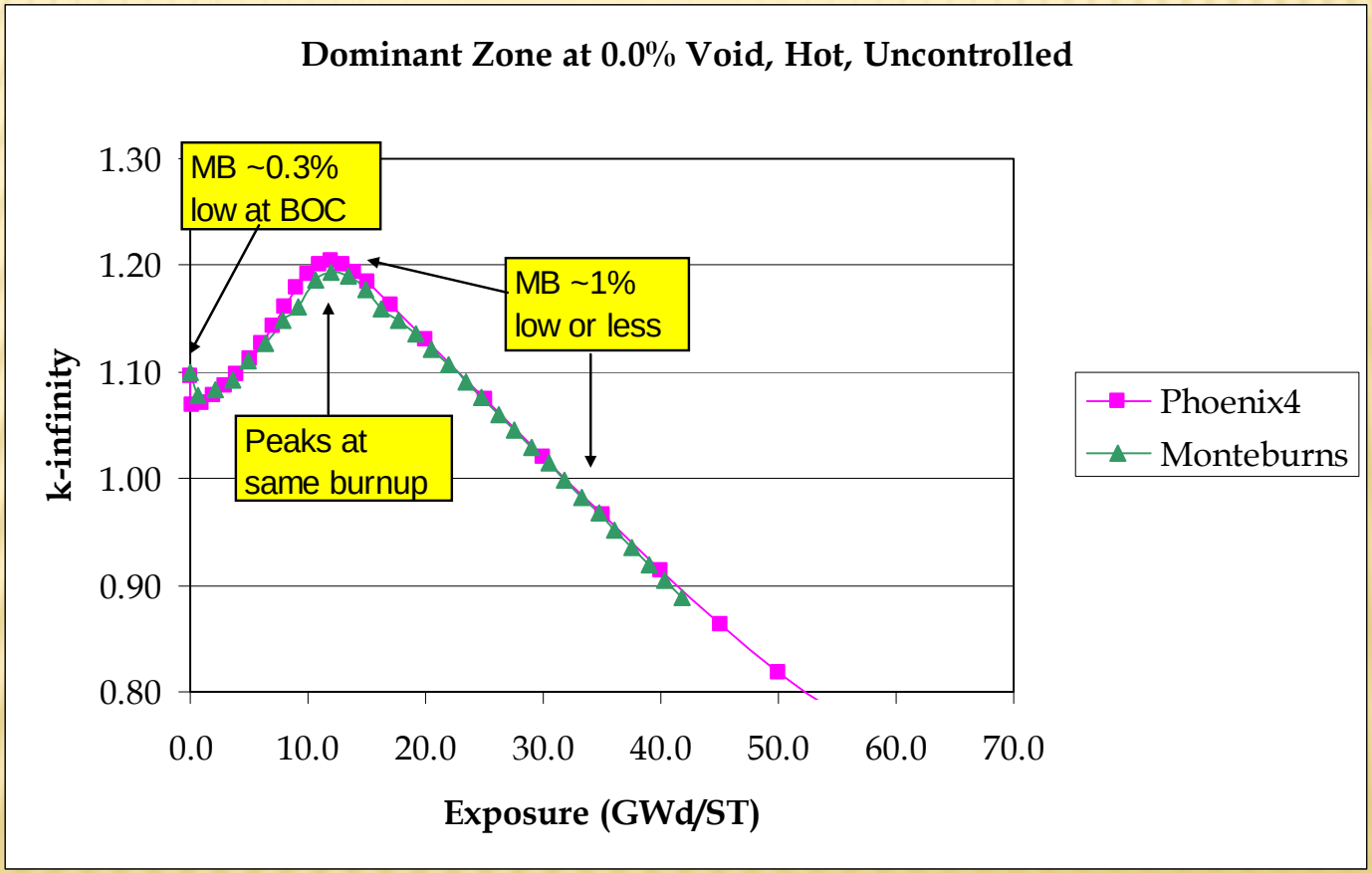

•Vanishing Zone (upper) axial region

Part-length "vanishing" rods

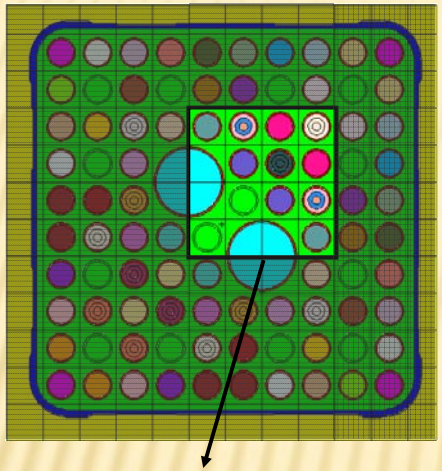
# PHOENIX Lattice Physics



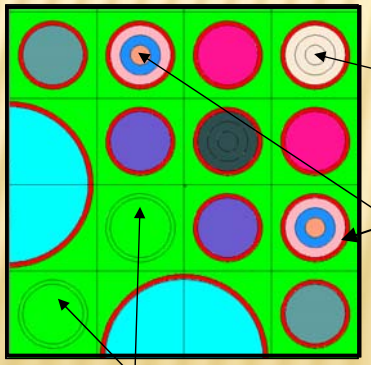
# PHOENIX vs MCNP5/MONTEBURNS comparisons



# Minor Actinide "Spiking"



One of several ideas:
"Use MA as burnable absorbers"

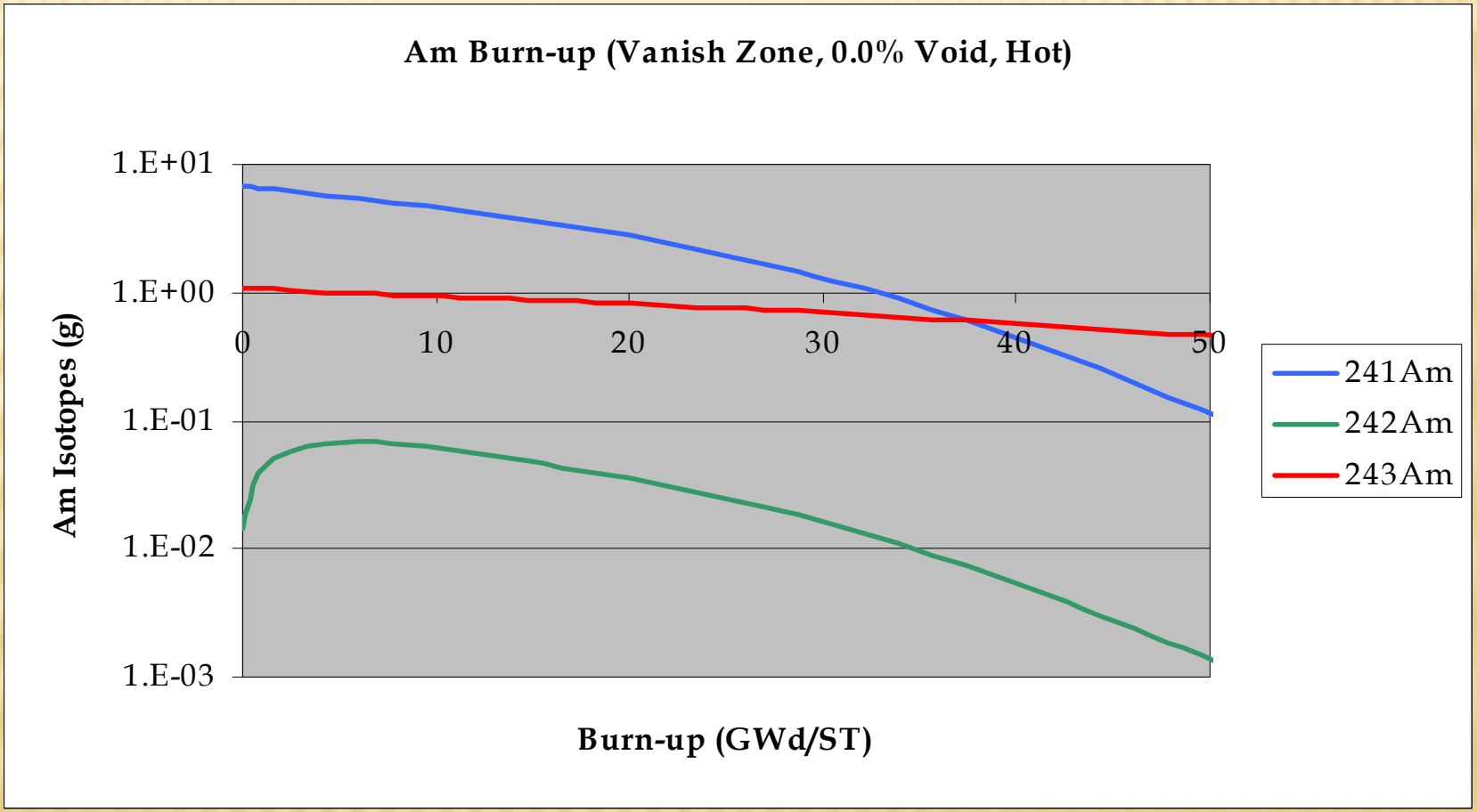


Gad Pin

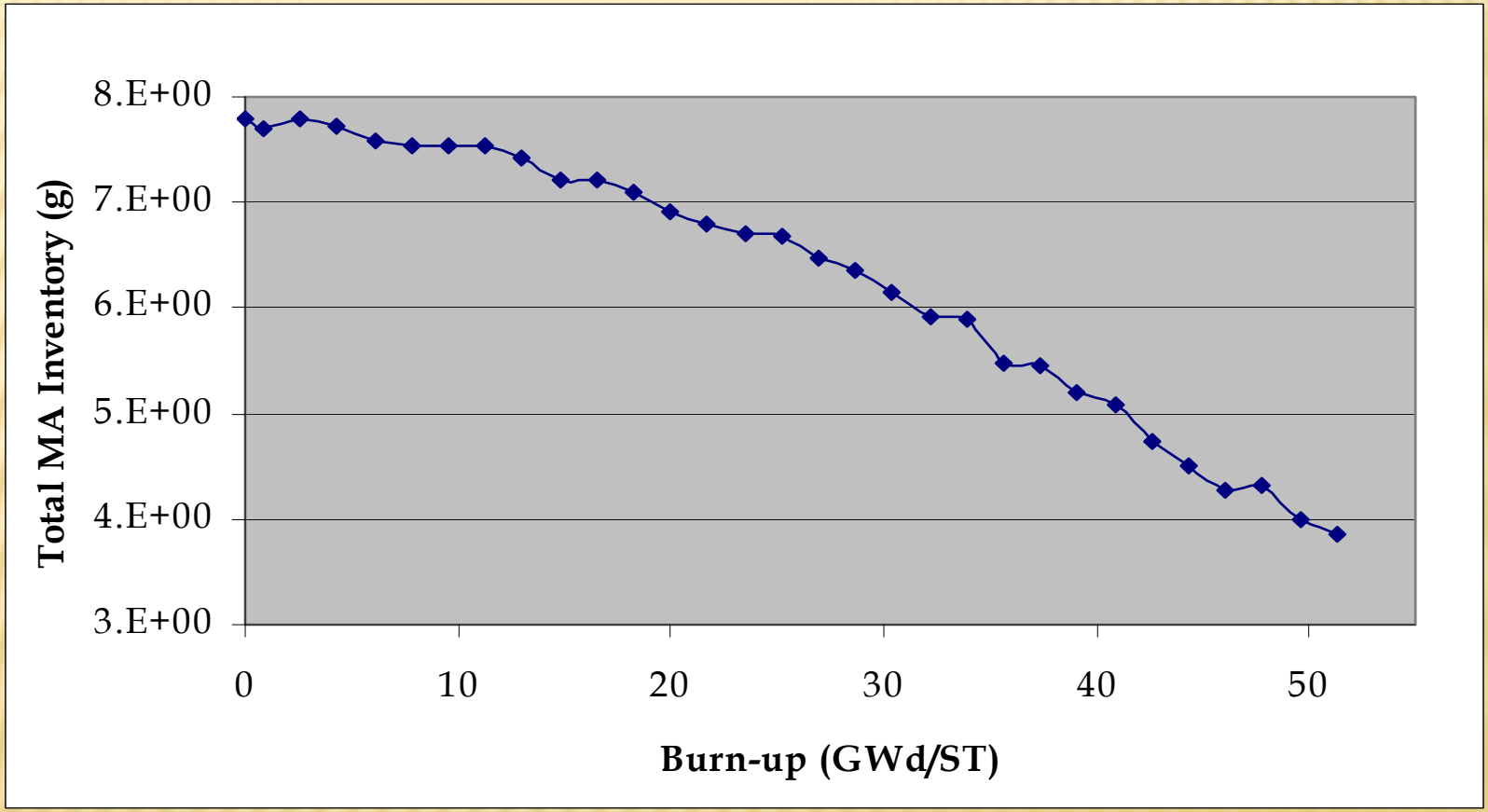
Two Symmetrically Located Am-spiked pins

vanished rods (clad and fuel set to $H_2O$)

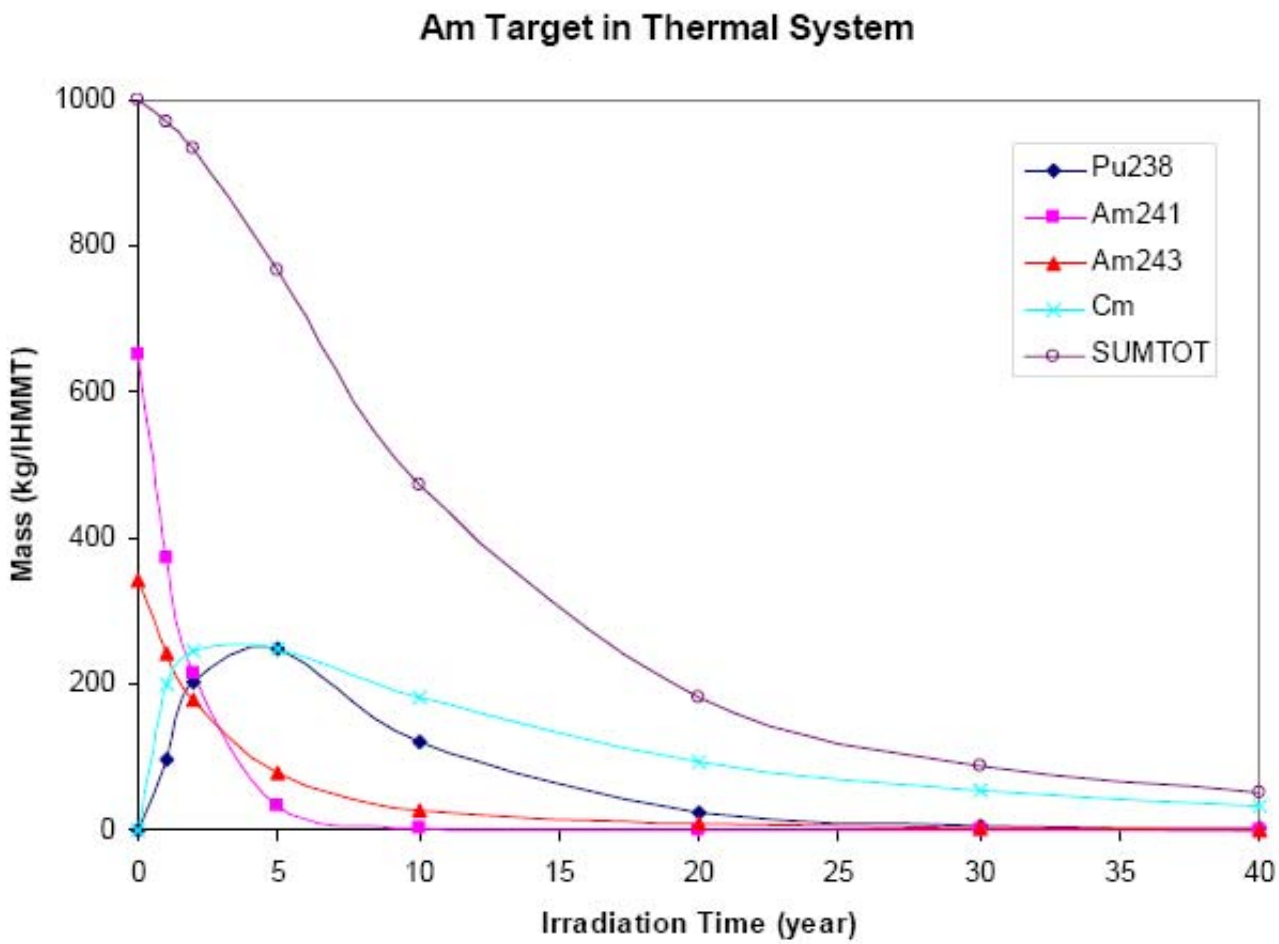
# Proof of principle – favorable trends



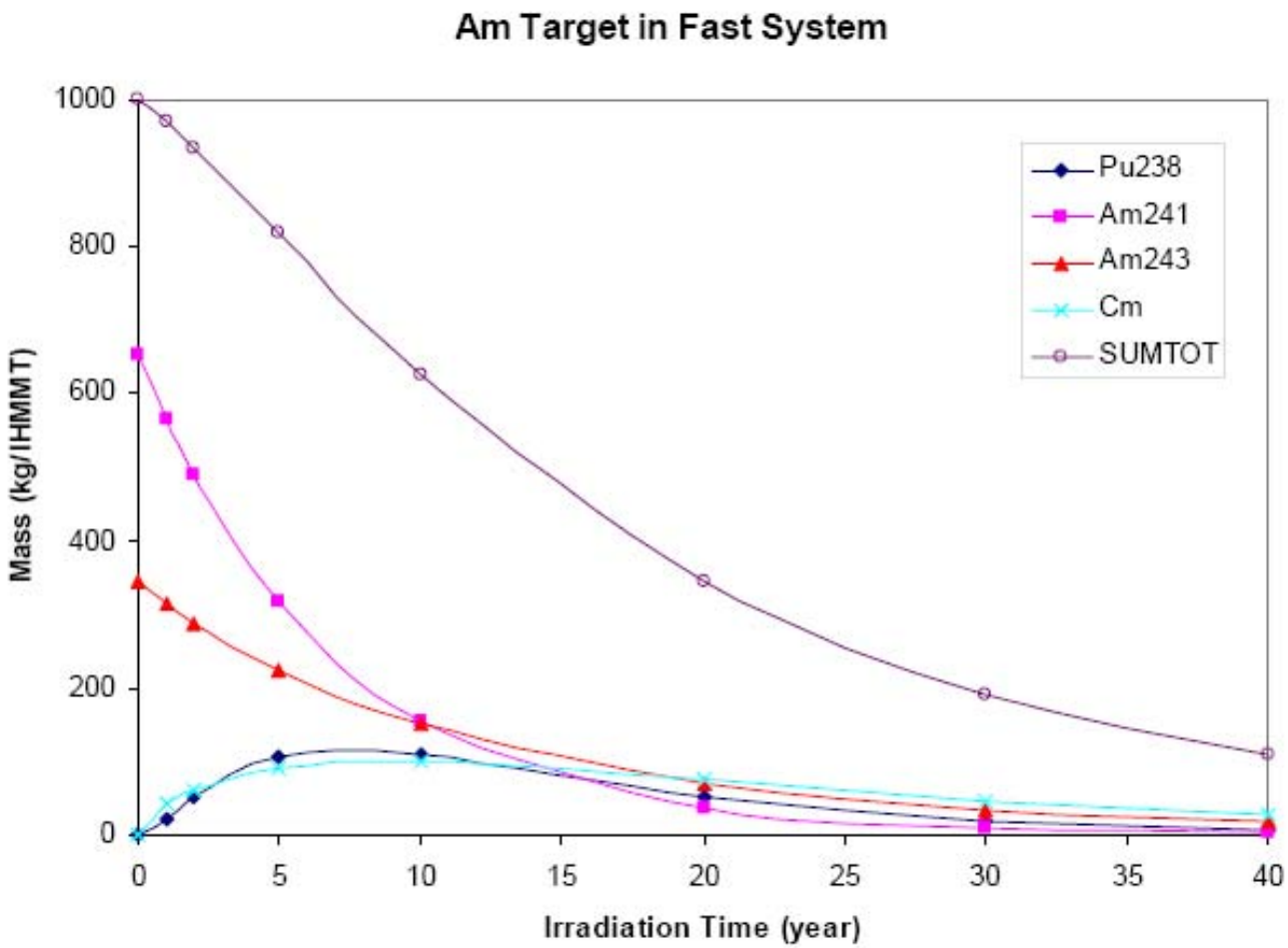
# MA inventory (excluding U and Pu)



# Consistent with other works… (Hill, et.al)



# Contrast to Fast System… (Hill, et.al)



# Our focus versus other studies…

- Several studies on homogeneous and heterogeneous recycling options have been done.
- Work is well summarized in ANL compendium report (Taiwo and Hill, 2007) which provides additional references to a number of detailed reports on the CORAIL, CONFU, Inert-Matrix, and various other recycling strategies.
- Research performed so far provides an excellent overview of the potential of LWR recycling strategies.

Most of the prior research, however, does not typically include **full-core analyses** and does not focus upon **BWRs** or upon **optimization** which are the primary emphases of the work herein reported and what pertains to americium-spiked lattices

# Nuclear Fuel Management Optimization

- Out of Core Optimization (Multi-Cycle)
- In-Core Optimization (Single Cycle)
- Within Bundle
  - Radial Optimization of Lattices (done)
  - Coupling to Core-Wide (evolving)
  - Axial Design (evolving)
- Coupling all of the above

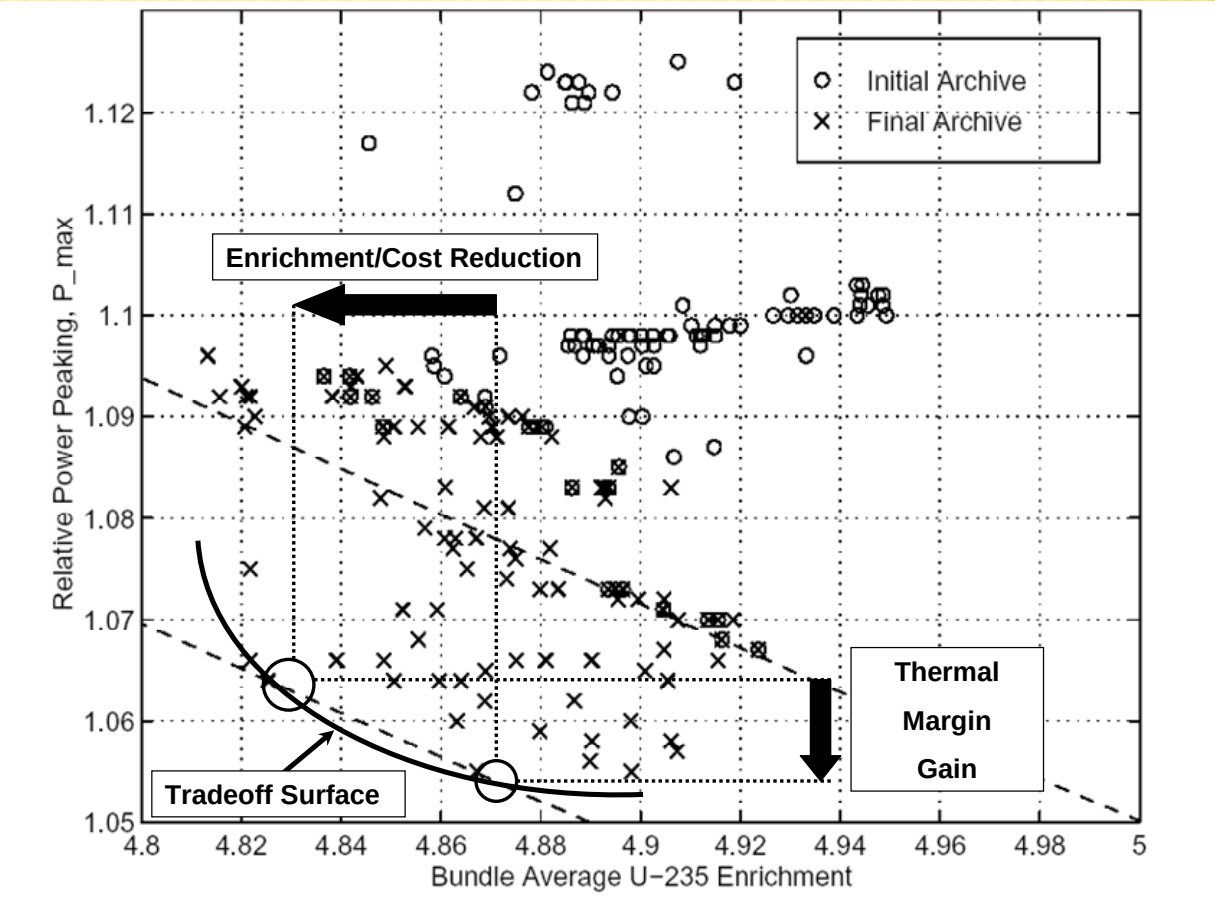
Most Mature!

Evolving!

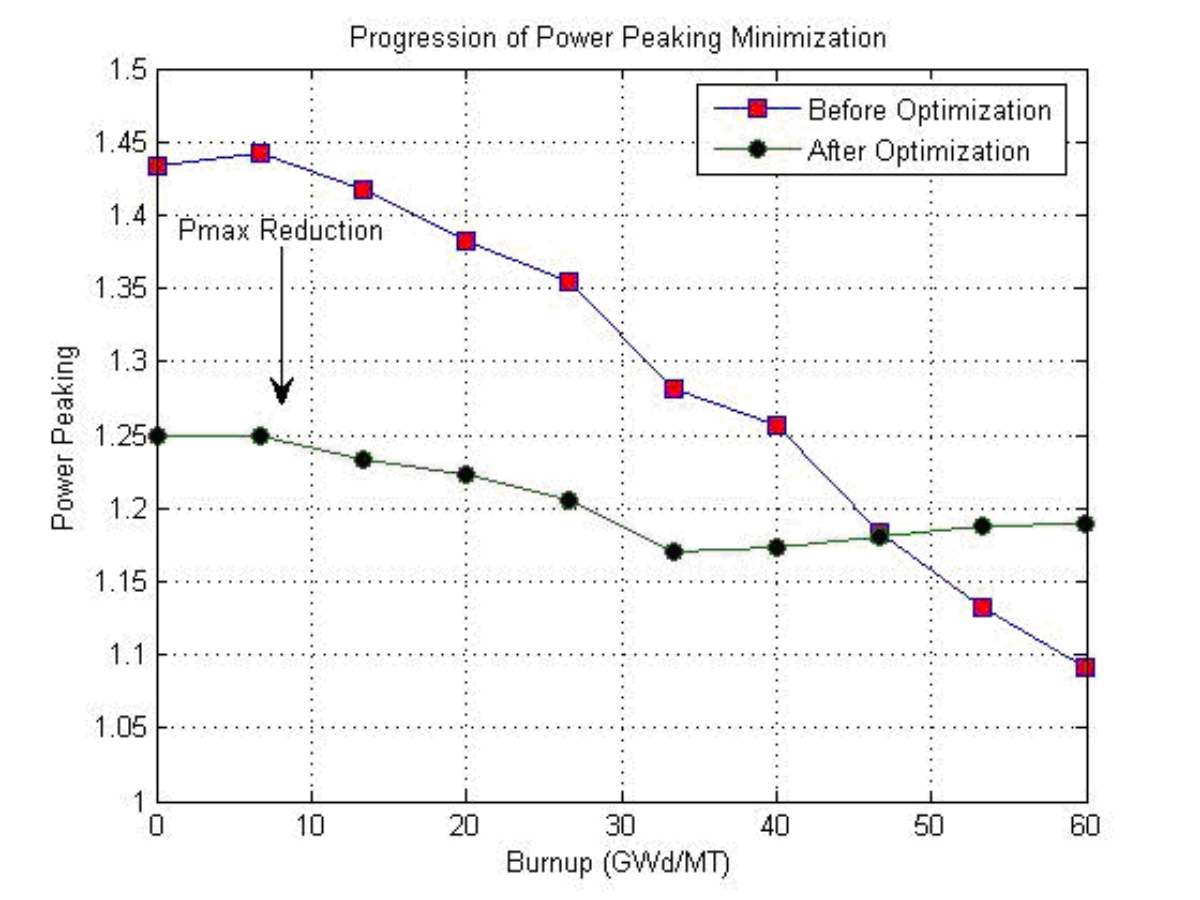
The Future!

# FORMOSA-L Optimization

- Family of NCSU EPRC codes (FORMOSA-P, FORMOSA-B)
- Based on Simulated Annealing, L=Lattice, Multi-Objective Capabilities

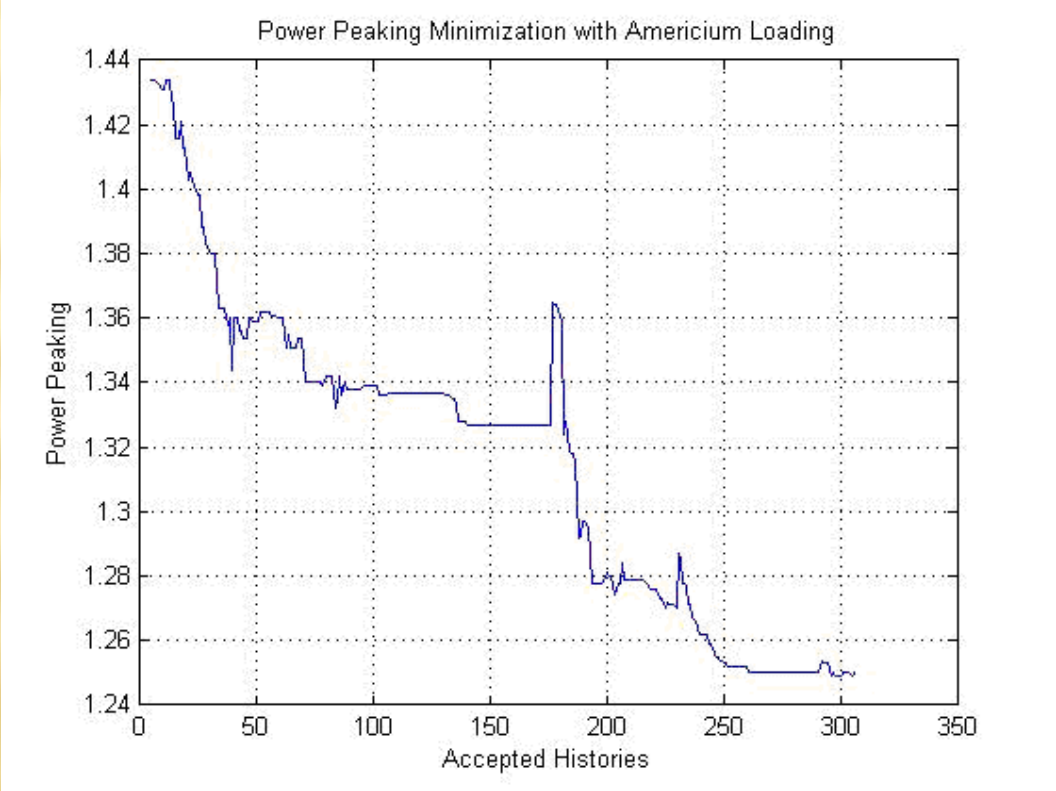


# FORMOSA-L Optimization



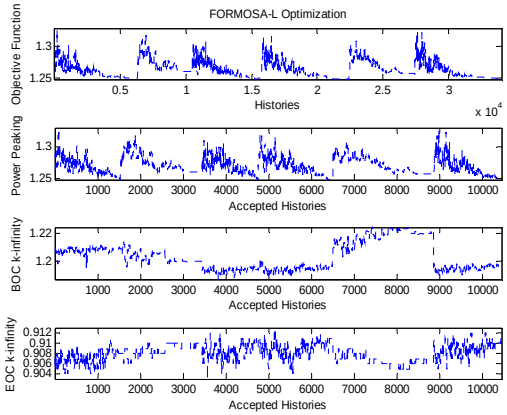
# FORMOSA-L Adaptation

- Developed coupling between FORMOSA-L and PHOENIX-4 (original couplings to CPM-2 and CASMO-3)
- Modification of the optimization engine to include minor actinides loading, such as americium alongside other standard parameters already in the code



# Initial Full-Core Tests

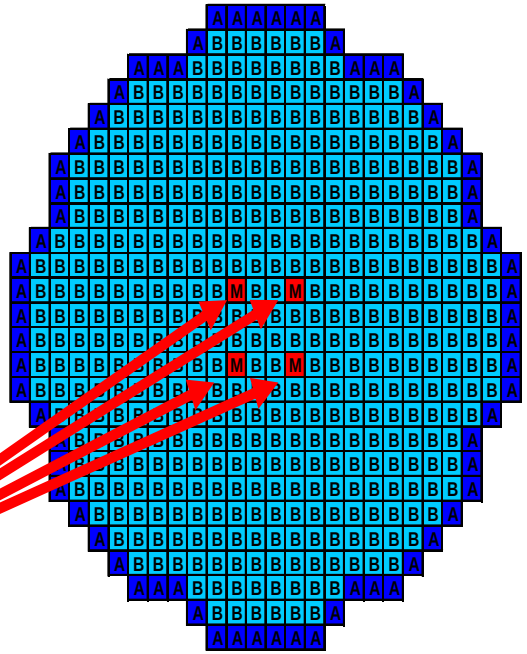
## Lattice Loading Optimization




Am-241 Target Pins

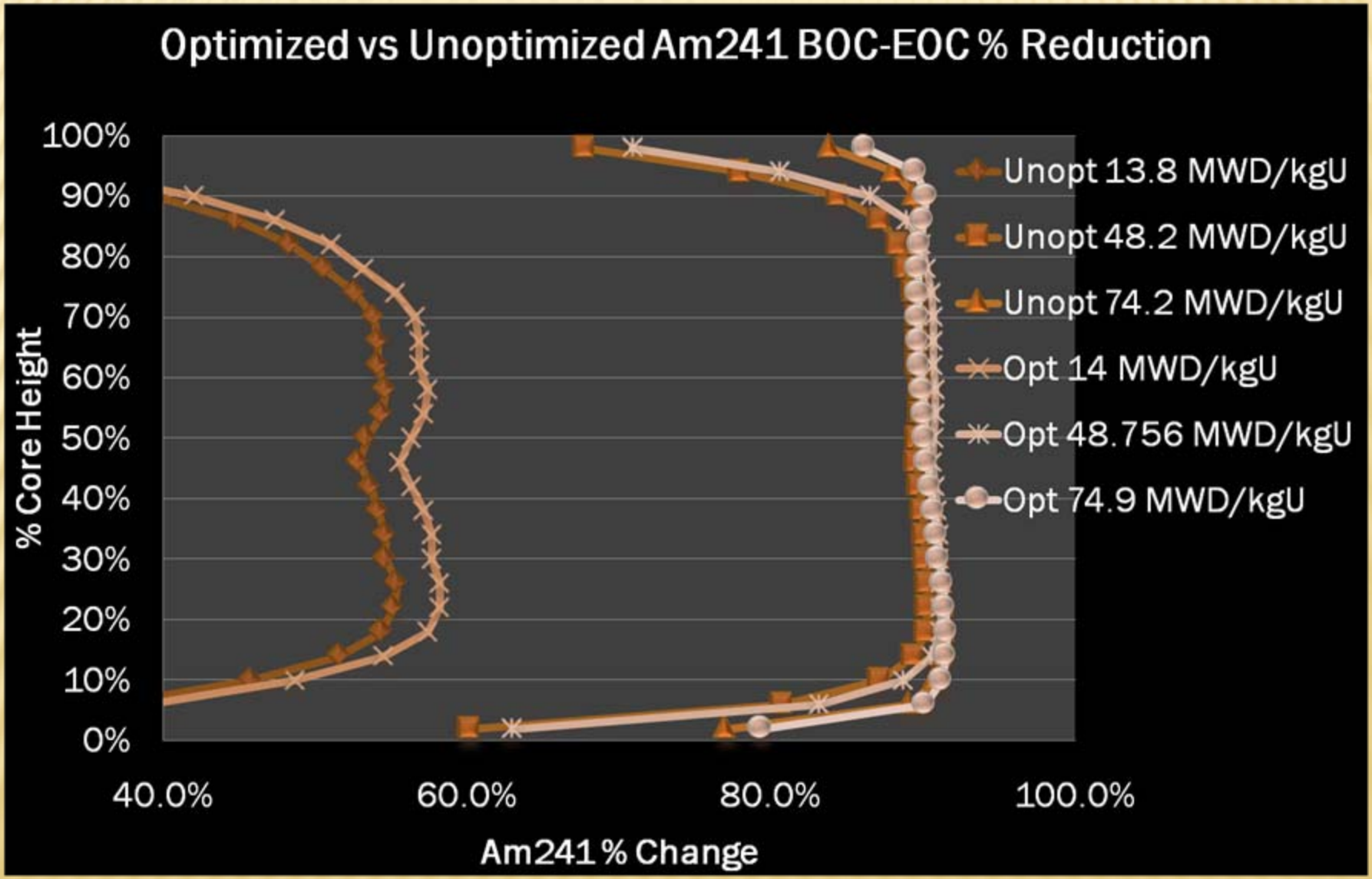
| | A | B | C | D | E | F | G | H | I | J |
|---|---|---|---|---|---|---|---|---|---|---|
| | 3.36 | 2.91 *6.01 | 4.21 | 2.70 *6.51 | 5.00 | 4.98 | 4.98 | 4.98 | 2.91 *6.01 | 3.50 |
| | 2.91 *6.01 | 5.00 | 3.49 | 3.49 | 4.98 | 5.00 | 5.00 | 5.00 | 2.80 *5.96 | 2.91 *6.01 |
| | 4.12 | 5.00 | 4.98 | 4.98 | 5.00 | 4.97 | 4.98 | 5.00 | 5.00 | 4.98 |
| | 2.70 *6.51 | 5.00 | 4.97 | - | WR | 4.97 | 5.00 | 4.98 | 5.00 | 4.98 |
| 5 | 4.97 | 4.97 | 5.00 | - | - | 3.36 | 4.97 | 4.97 | 5.00 | 4.98 |
| 6 | 4.98 | 4.97 | 5.00 | 5.00 | 3.36 | - | WR | 5.00 | 4.98 | 5.00 |
| 7 | 4.97 | 5.00 | 5.00 | 5.00 | 5.00 | - | - | 4.98 | 3.49 | 2.70 *6.51 |
| 8 | 2.70 *6.51 | 4.97 | 5.00 | 5.00 | 5.00 | 5.00 | 4.97 | 4.98 | 3.49 | 4.21 |
| 9 | 3.00 *6.10 | 2.70 *6.51 | 4.97 | 4.98 | 4.97 | 4.97 | 5.00 | 5.00 | 5.00 | 2.91 *6.01 |
| 10 | 3.50 | 3.00 *6.10 | 4.98 | 4.97 | 5.00 | 4.97 | 2.70 *6.51 | 4.12 | 2.91 *6.01 | 3.36 |

## 3D Full Core BWR Analysis

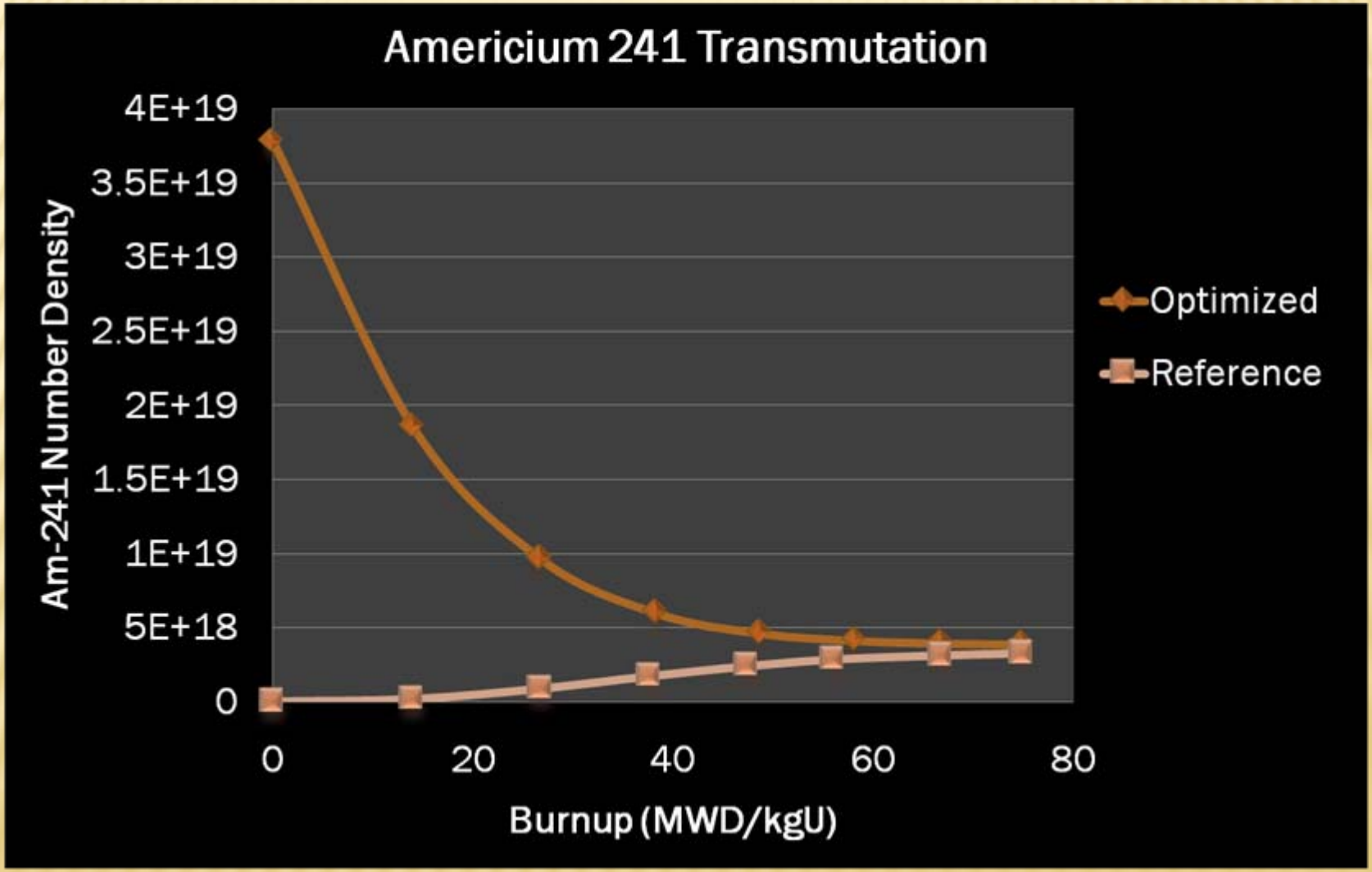


"Lead Test Assemblies"

# SIMULATION RESULTS



# AM-241 TRANSMUTATION - NUMBER DENSITY



# Upgraded Reference Model

- Originally available model delivered with software not very good or contemporary
- Created Reference 500-bundle 4-batch loadings
- 18-month operational cycles at full power.
- After 3 reloads, this core design begins to approach an equilibrium behavior.

# Upgraded Reference Model

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 13 | 38.7 | 38.4 | 39.1 | | | | | | | | | | |
| 12 | 35.6 | 35.5 | 37.7 | 38.8 | | | | | | | | | |
| 11 | 28.3 | 14.2 | 14.1 | 37.8 | 38.6 | 38.6 | 40.1 | | | | | | |
| 10 | 0.0 | 0.0 | 14.4 | 14.6 | 14.4 | 37.6 | 37.7 | 40.4 | | | | | |
| 9 | 13.1 | 25.6 | 0.0 | 25.5 | 14.0 | 14.7 | 36.0 | 38.0 | 40.1 | | | | |
| 8 | 24.3 | 0.0 | 13.3 | 12.7 | 24.8 | 0.0 | 13.4 | 35.1 | 38.0 | 40.4 | | | |
| 7 | 0.0 | 24.0 | 0.0 | 12.5 | 0.0 | 12.2 | 0.0 | 13.4 | 36.0 | 37.7 | 40.1 | | |
| 6 | 25.0 | 0.0 | 23.3 | 0.0 | 23.7 | 0.0 | 12.2 | 0.0 | 14.5 | 37.6 | 38.6 | | |
| 5 | 12.8 | 22.0 | 0.0 | 25.0 | 14.2 | 23.7 | 0.0 | 24.8 | 14.0 | 14.4 | 38.6 | | |
| 4 | 22.0 | 0.0 | 23.1 | 12.9 | 25.0 | 0.0 | 23.7 | 12.7 | 25.5 | 14.6 | 37.8 | 38.8 | |
| 3 | 0.0 | 22.3 | 0.0 | 23.1 | 0.0 | 23.3 | 0.0 | 13.3 | 0.0 | 14.4 | 14.1 | 37.7 | 39.1 |
| 2 | 23.7 | 0.0 | 22.3 | 0.0 | 22.0 | 0.0 | 24.0 | 0.0 | 25.6 | 0.0 | 14.2 | 35.5 | 38.4 |
| 1 | 34.7 | 23.7 | 0.0 | 22.0 | 12.8 | 25.0 | 0.0 | 24.3 | 13.1 | 0.0 | 28.3 | 35.6 | 38.7 |

**Legend**

Burnup: MWd/kgU = GWd/MTU

- Fresh Fuel
- Once Burnt
- Twice Burnt
- Thrice Burnt

# Upgraded Bundle Design

Upper Blanket with vanishing zone (6.9")

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 0.71 | 0.71 | 0.71 | 0.71 | 0.71 | 0.71 | 0.71 | 0.71 | 0.71 | 0.71 |
| 0.71 | VAN | 0.71 | VAN | 0.71 | 0.71 | VAN | 0.71 | VAN | 0.71 |
| 0.71 | 0.71 | 0.71 | 0.71 | 0.71 | 0.71 | 0.71 | 0.71 | 0.71 | 0.71 |
| 0.71 | VAN | 0.71 | 0.71 | 0.71 | H2O | H2O | 0.71 | VAN | 0.71 |
| 0.71 | 0.71 | 0.71 | 0.71 | VAN | H2O | H2O | 0.71 | 0.71 | 0.71 |
| 0.71 | 0.71 | 0.71 | H2O | H2O | VAN | 0.71 | 0.71 | 0.71 | 0.71 |
| 0.71 | VAN | 0.71 | H2O | H2O | 0.71 | 0.71 | 0.71 | VAN | 0.71 |
| 0.71 | 0.71 | 0.71 | 0.71 | 0.71 | 0.71 | 0.71 | 0.71 | 0.71 | 0.71 |
| 0.71 | VAN | 0.71 | VAN | 0.71 | 0.71 | VAN | 0.71 | VAN | 0.71 |
| 0.71 | 0.71 | 0.71 | 0.71 | 0.71 | 0.71 | 0.71 | 0.71 | 0.71 | 0.71 |

Upper Blanket

Upper Vanishing Zone (42")

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 2.00 | 2.80 | 3.60 | 4.40 | 4.40 | 4.40 | 3.95 | 3.60 | 2.80 | 2.00 |
| 2.80 | VAN | 3.95 | VAN | 3.95 | 3.95 | VAN | 3.95 | VAN | 2.80 |
| 3.60 | 3.95 | 4.40/5.00 | 3.95 | 4.40/5.00 | 4.90 | 4.40 | 4.40/4.00 | 3.95 | 3.95 |
| 4.40 | VAN | 3.95 | 4.40/2.00 | 4.90 | H2O | H2O | 4.40 | VAN | 4.40 |
| 4.40 | 3.95 | 4.40/5.00 | 4.90 | VAN | H2O | H2O | 4.40/5.00 | 4.40 | 4.40 |
| 4.40 | 3.95 | 4.90 | H2O | H2O | VAN | 4.40 | 4.40 | 4.40/4.00 | 4.40 |
| 3.95 | VAN | 4.40 | H2O | H2O | 4.40 | 4.40 | 4.40/4.00 | VAN | 4.40 |
| 3.60 | 3.95 | 4.40/4.00 | 4.40 | 4.40/5.00 | 4.40 | 4.40/4.00 | 4.40 | 3.95/4.00 | 3.95 |
| 2.80 | VAN | 3.95 | VAN | 4.40 | 4.40/4.00 | VAN | 3.95/4.00 | VAN | 3.60 |
| 2.00 | 2.80 | 3.95 | 4.40 | 4.40 | 4.40 | 4.40 | 3.95 | 3.60 | 2.00 |

Vanishing Zone

Lower Dominant Zone (90")

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 2.00 | 2.80 | 3.60 | 4.40 | 4.40 | 4.40 | 3.95 | 3.60 | 2.80 | 2.00 |
| 2.80 | 4.40 | 3.95 | 4.90 | 3.95 | 3.95 | 4.90 | 3.95 | 4.40 | 2.80 |
| 3.60 | 3.95 | 4.40/5.00 | 3.95 | 4.40/5.00 | 4.90 | 4.40 | 4.40/4.00 | 3.95 | 3.95 |
| 4.40 | 4.90 | 3.95 | 4.40/2.00 | 4.90 | H2O | H2O | 4.40 | 4.90 | 4.40 |
| 4.40 | 3.95 | 4.40/5.00 | 4.90 | 4.40 | H2O | H2O | 4.40/5.00 | 4.40 | 4.40 |
| 4.40 | 3.95 | 4.90 | H2O | H2O | 4.40 | 4.40 | 4.40 | 4.40/4.00 | 4.40 |
| 3.95 | 4.90 | 4.40 | H2O | H2O | 4.40 | 4.40 | 4.40/4.00 | 4.90 | 4.40 |
| 3.60 | 3.95 | 4.40/4.00 | 4.40 | 4.40/5.00 | 4.40 | 4.40/4.00 | 4.40 | 3.95/4.00 | 3.95 |
| 2.80 | 4.40 | 3.95 | 4.90 | 4.40 | 4.40/4.00 | 4.90 | 3.95/4.00 | 4.40 | 3.60 |
| 2.00 | 2.80 | 3.95 | 4.40 | 4.40 | 4.40 | 4.40 | 3.95 | 3.60 | 2.00 |

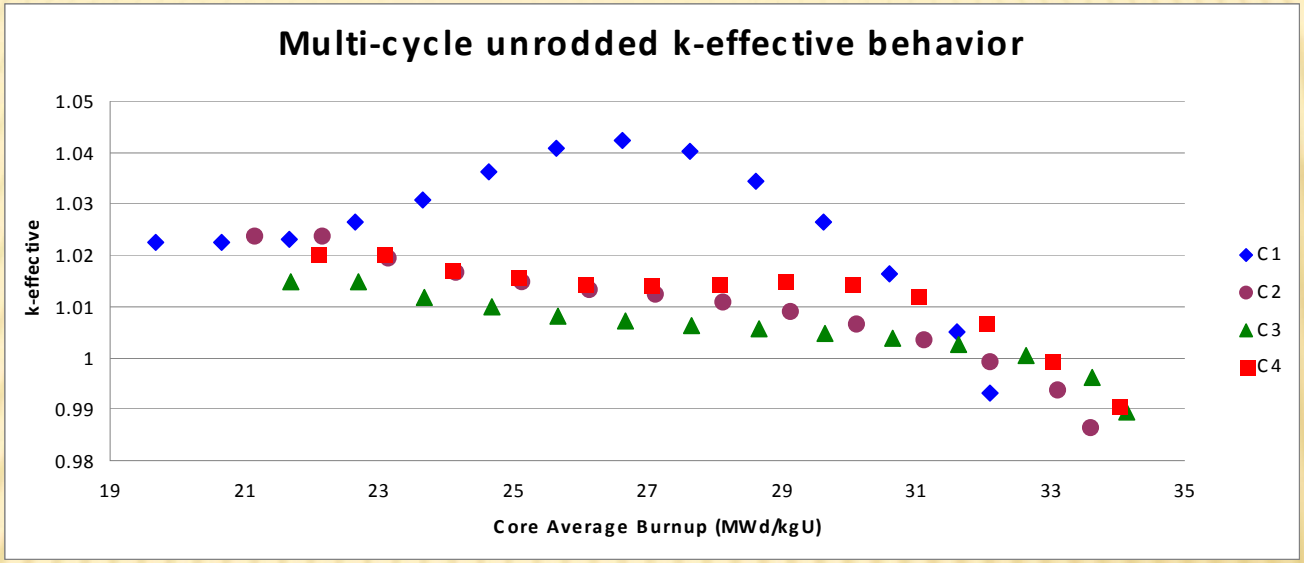
Dominant Zone

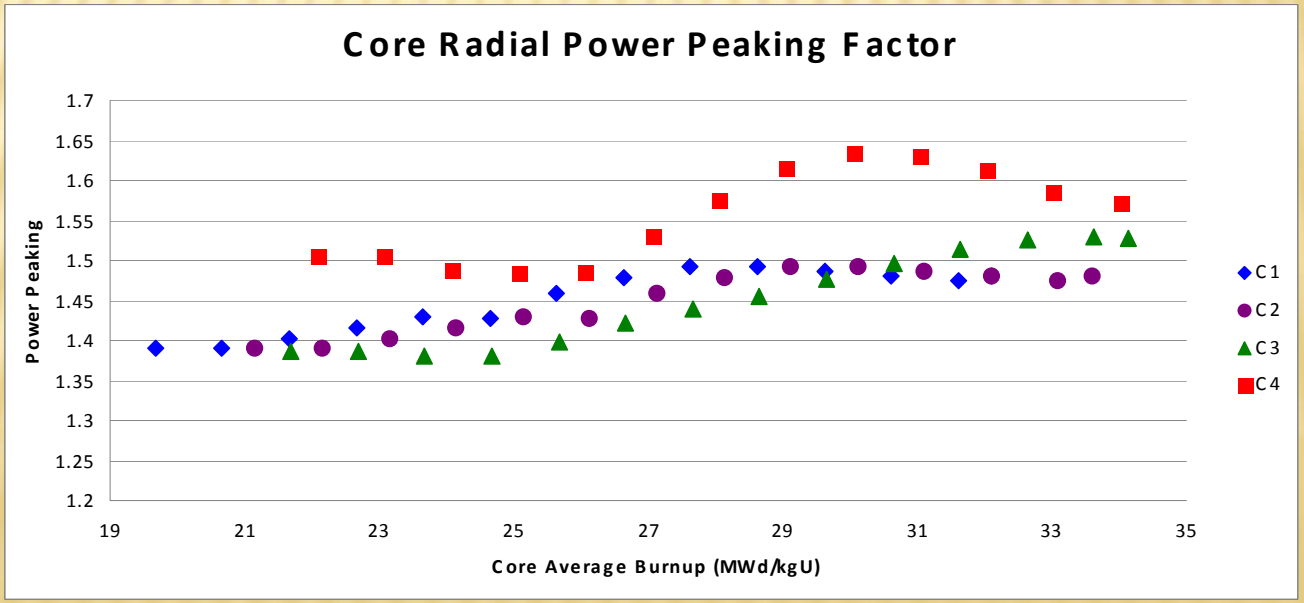
Lower Blanket (6")

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 0.71 | 0.71 | 0.71 | 0.71 | 0.71 | 0.71 | 0.71 | 0.71 | 0.71 | 0.71 |
| 0.71 | 0.71 | 0.71 | 0.71 | 0.71 | 0.71 | 0.71 | 0.71 | 0.71 | 0.71 |
| 0.71 | 0.71 | 0.71 | 0.71 | 0.71 | 0.71 | 0.71 | 0.71 | 0.71 | 0.71 |
| 0.71 | 0.71 | 0.71 | 0.71 | 0.71 | H2O | H2O | 0.71 | 0.71 | 0.71 |
| 0.71 | 0.71 | 0.71 | 0.71 | 0.71 | H2O | H2O | 0.71 | 0.71 | 0.71 |
| 0.71 | 0.71 | 0.71 | H2O | H2O | 0.71 | 0.71 | 0.71 | 0.71 | 0.71 |
| 0.71 | 0.71 | 0.71 | H2O | H2O | 0.71 | 0.71 | 0.71 | 0.71 | 0.71 |
| 0.71 | 0.71 | 0.71 | 0.71 | 0.71 | 0.71 | 0.71 | 0.71 | 0.71 | 0.71 |
| 0.71 | 0.71 | 0.71 | 0.71 | 0.71 | 0.71 | 0.71 | 0.71 | 0.71 | 0.71 |
| 0.71 | 0.71 | 0.71 | 0.71 | 0.71 | 0.71 | 0.71 | 0.71 | 0.71 | 0.71 |

Lower Blanket

# Multi-Cycle Behavior



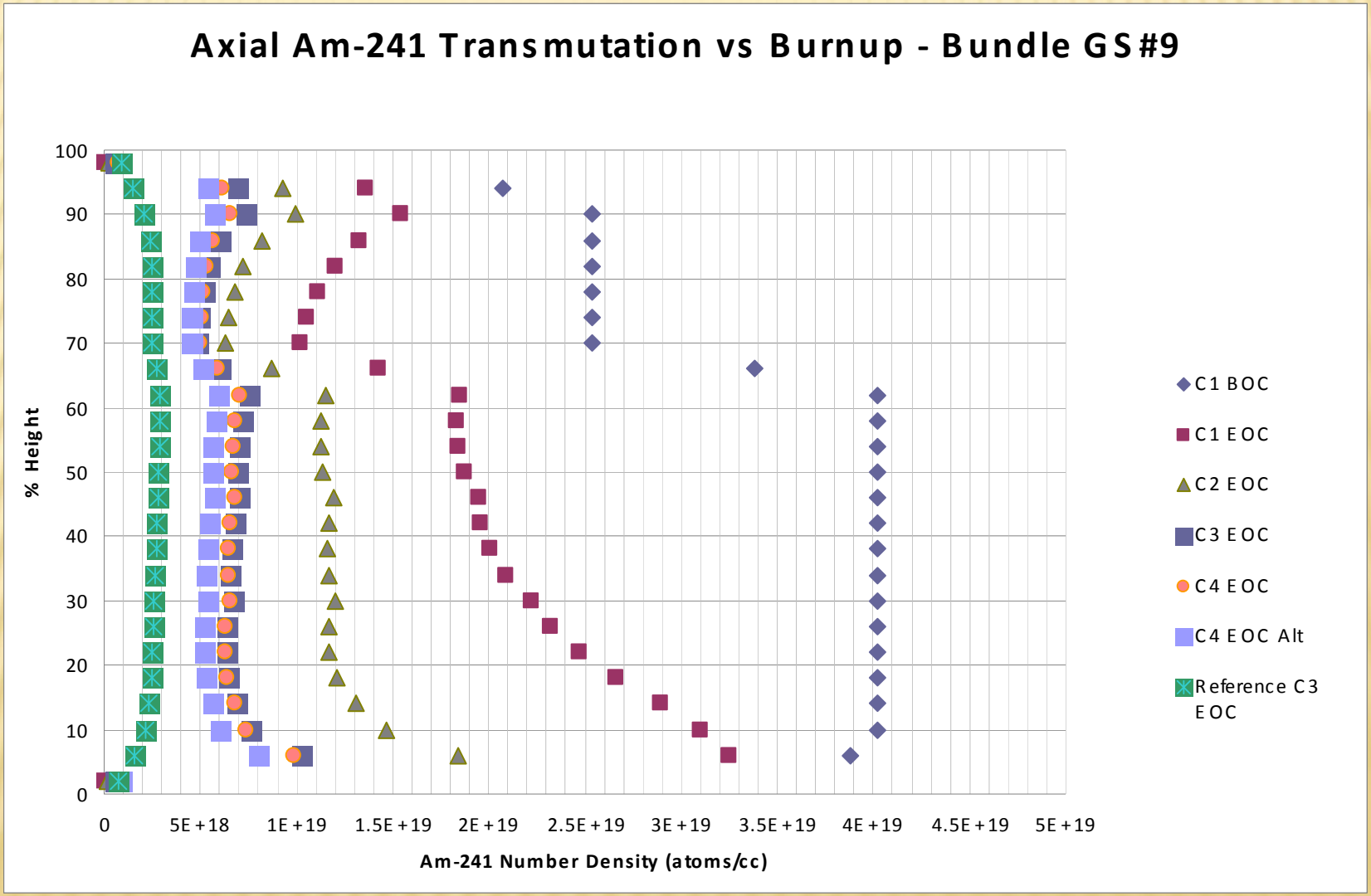
# Optimized "Spiked Bundle"

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 2.19% | 5.00% | 5.00% | 5.00% | 5.00% | 4.99% | 4.99% | 5.00% | 4.99% | 2.19% |
| 5.00% | 5.00% | 4.99% | 4.89% | 5.00% | 5.00% | 4.89% | 5.00% | 5.00% | 5.00% |
| 5.00% | 4.99% | 2.9(5%) | 4.99% | 2.9(5%) | 2.7(4%) | 4.99% | 4.89% | 4.99% | 4.99% |
| 5.00% | 4.89% | 4.99% | 3.0(3%) | 4.89% | H2O | H2O | 5.00% | 4.89% | 5.00% |
| 5.00% | 5.00% | 2.9(5%) | 4.89% | 5.00% | H2O | H2O | 2.9(5%) | 5.00% | 5.00% |
| 4.99% | 5.00% | 2.7(4%) | H2O | H2O | 5.00% | 5.00% | 5.00% | 2.7(4%) | 5.00% |
| 4.99% | 4.89% | 4.99% | H2O | H2O | 5.00% | 5.00% | 2.7(4%) | 4.89% | 5.00% |
| 5.00% | 5.00% | 4.89% | 5.00% | 2.9(5%) | 5.00% | 2.7(4%) | 5.00% | 2.8(4%) | 4.99% |
| 4.99% | 5.00% | 4.99% | 4.89% | 5.00% | 2.7(4%) | 4.89% | 2.8(4%) | 5.00% | 5.00% |
| 2.19% | 5.00% | 4.99% | 5.00% | 5.00% | 5.00% | 5.00% | 4.99% | 5.00% | 2.19% |

# Loading strategies for spiked bundles

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 13 | | | | | | | | | | | | | |
| 12 | | | | | | | | | | | | | |
| 11 | | | | | | | | | | | | | |
| 10 | | GS#13 C1 | | | | | | GR#9 C4 | | | | | |
| 9 | | | | | | | | | | | | | |
| 8 | | | GS#13 C2 | | | GR#13 C4 Alt | | | | GR#13 C4 | | | |
| 7 | | | | | | | | | | | | | |
| 6 | | | | GS#9 C3 | | | | GR#13 C4 Alt | | | | | |
| 5 | | | | | | | | | | | | | |
| 4 | | | | | | GS#13 C3 | | | | | | | |
| 3 | | | | | | | | GS#9 C2 | | | | | |
| 2 | | | | | | | | | | GS#9 C1 | | | |
| 1 | | | | | | | | | | | | | |

# Am-241 Transmutation Results



# Conclusions

- Note greater efficiency with which earlier cycles destroy the planted Am-241. In other words, C1 is more efficient than C2, which is more efficient than C3, which is more efficient than C4, whereby the effects of lattice loading optimization are more meaningful earlier in the process when there is a greater inventory.
- A key conclusion is the ability to eliminate roughly 89% of the planted Am-241 inventory within four cycles
- Should core designers deviate from standard practice, the "Alternate C4" placement of the spiked bundles in their final tour increases the incineration level to about 92% as an axial average.

# Conclusions

- Cold shutdown margin (SDM) calculations with and without the spiked bundles revealed insignificant changes at the limiting conditions and changes of the order of 0.01% to 0.05% in SDM otherwise throughout the cycle.
- When examining individual cells, it was noted that ~1% degrading of the SDM can occur in spiked cells but these cells had very large margins and were not limiting.

# Current Endeavors

- Employment of NESTLE code for future studies in actinide management
  - BWR applications (Jack Galloway)
  - PWR applications (Hermilo Hernandez)
  - CANDU applications (Mark Massie – Summer'08)
    - Shane Hart (Fall'08)

# Any Questions?