Rapid Comparative Quantitative Analysis of Nuclear Fuel Cycles

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Motivation

- Future of nuclear power uncertain
- Abundance of fuel cycle options:
  - Fuel isotope mix?
  - Fuel recycling: Once-Through/Tiered?
  - Reactor type: Fast/Thermal?
  - Reloading: Single/Batch-Mode?
- Question: Which cycle to use?

Project Aims

- Difficult to compare nuclear cycles
- Focus typically on 2-3 cycle comparison
- Use lumped model to quickly simulate large number of disparate cycles
- Primary aim:

'Establish a framework of metrics allowing direct comparison between different nuclear cycles'

Reactor Model

- First-order lumped transient model
- First developed to model fast ADSRs by David Coates
- Model adapted to run variety of thermal/fast cycles
- Numerically solves differential equation for each of 49 separate fuel isotopes

Metric Overview

- 3 major metric groups:
  - Efficiency/Sustainability
  - Waste Toxicity
  - Proliferation Hardness/Resistance
- Parity
  - Single v. Multi-tier cycles
  - Thermal v. Fast cycles
  - 50,000GWd energy limit
  - Cycles repeated to reach limit

Sustainability

- Can calculate ‘potential’ of any atom population
- Allows definition of ‘cycle efficiency’

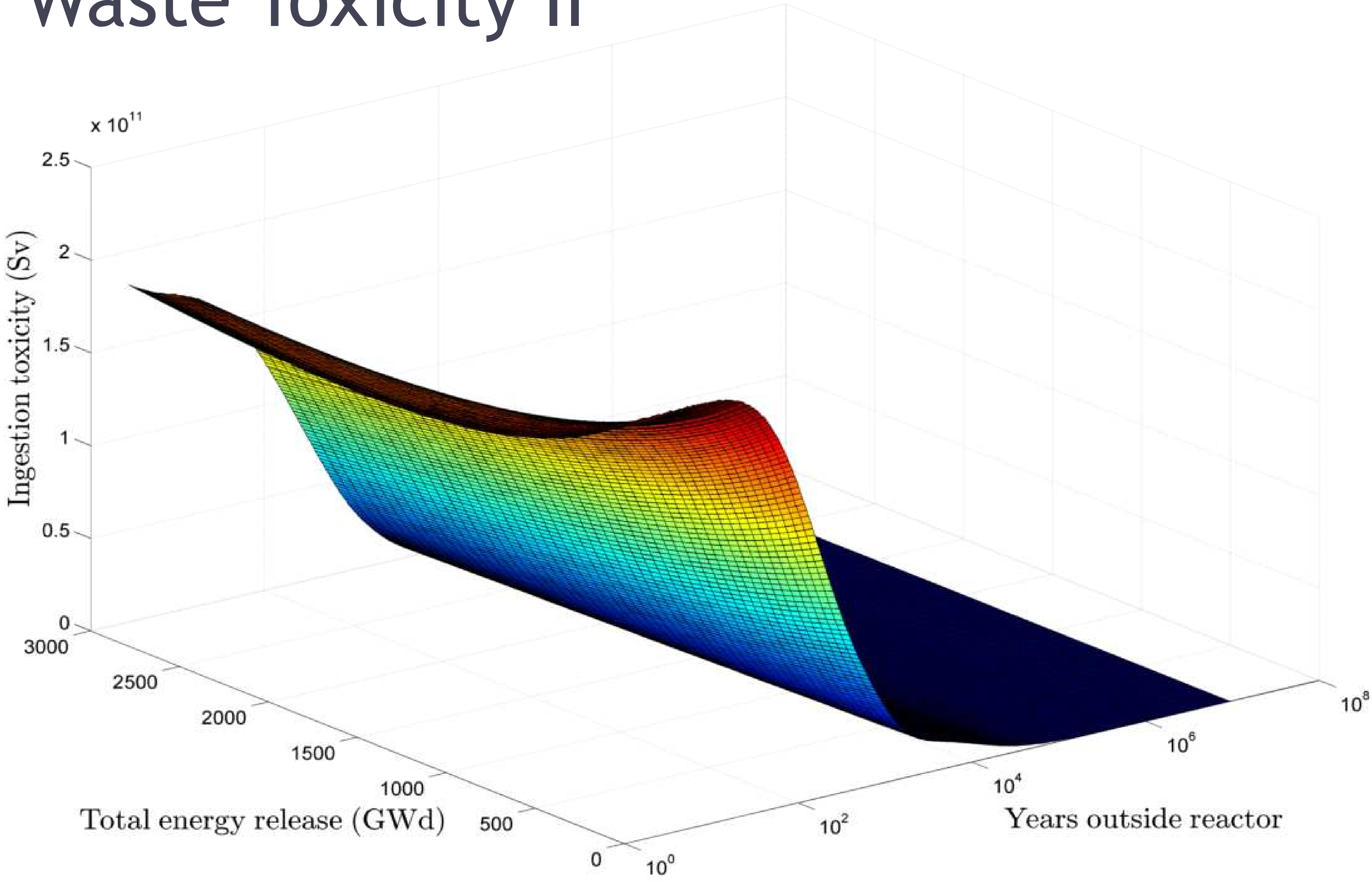
$$\eta_{\text{nuc}} = \frac{\langle \text{Fuel} \rangle - \langle \text{Waste} \rangle}{\langle \text{Fuel} \rangle}$$

- High nuclear efficiency implies cycle extracts high proportion of available energy

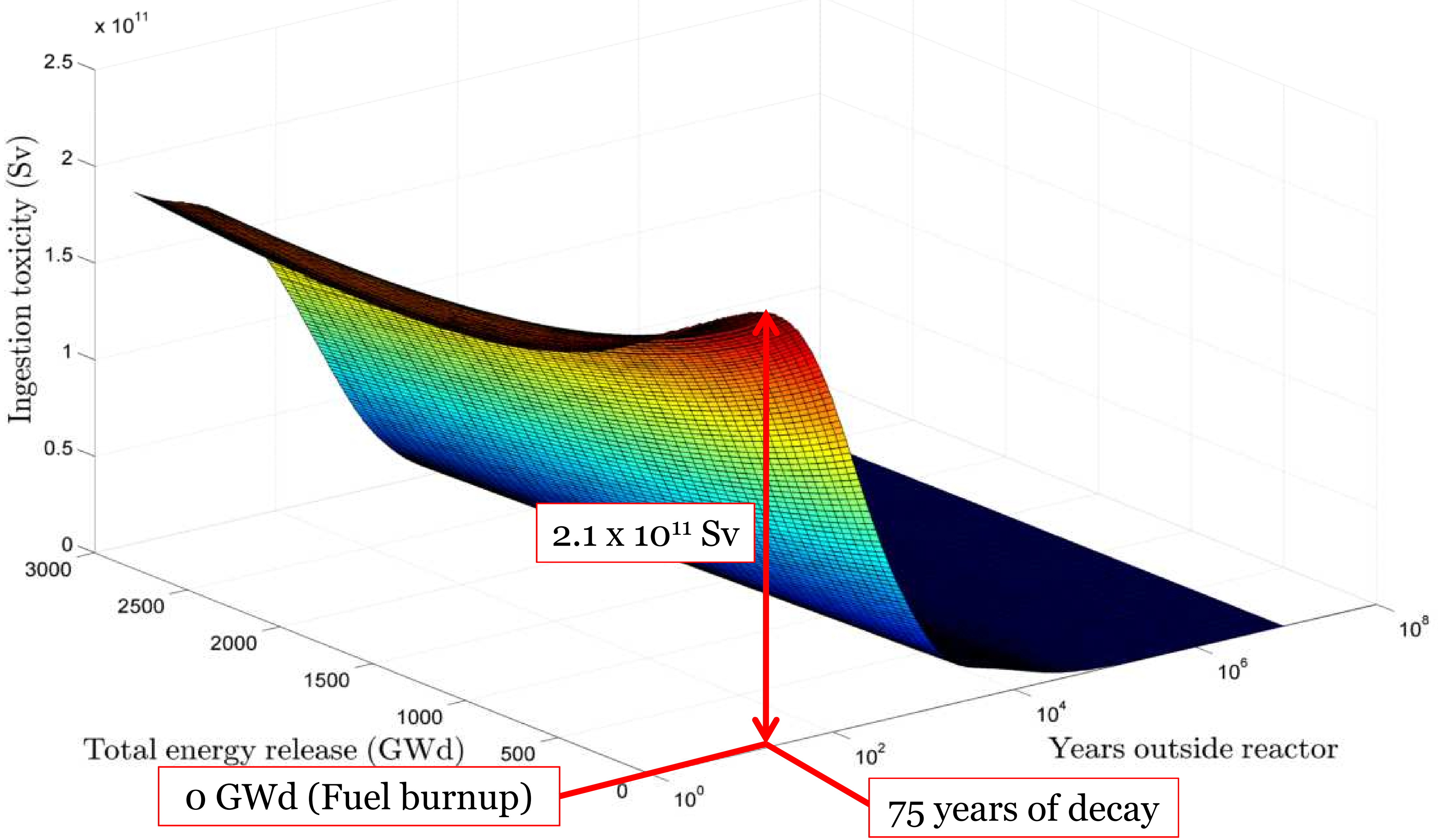
Waste Toxicity I

- Waste composition determined through application of Bateman equations using NEA data
- Ingestive toxicity determined through multiplication by ICRP figures (ICRP 72)
- 9 million year decay period modelled with results verified through comparison to NEA code results

Waste Toxicity II



Waste Toxicity II



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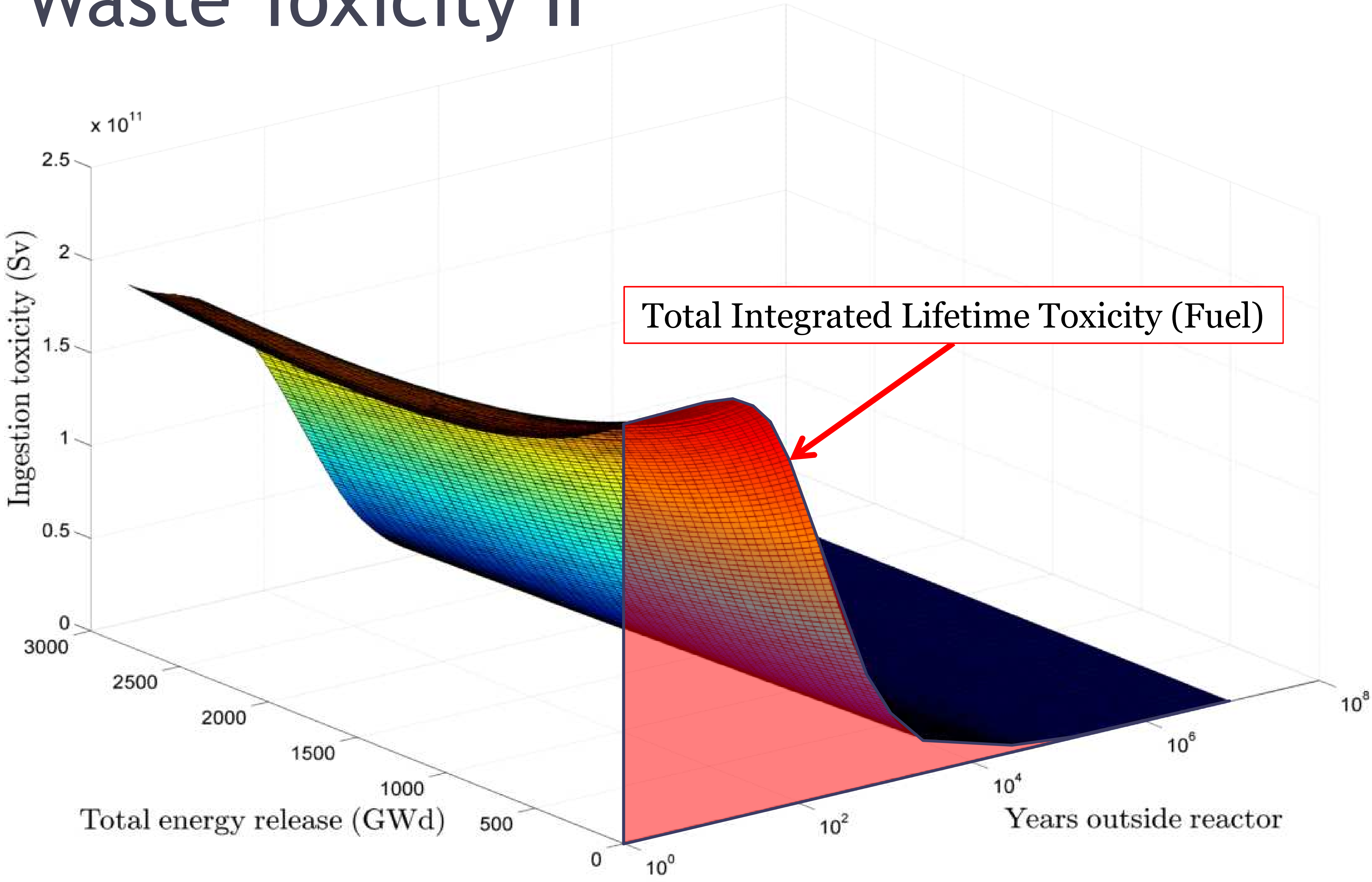

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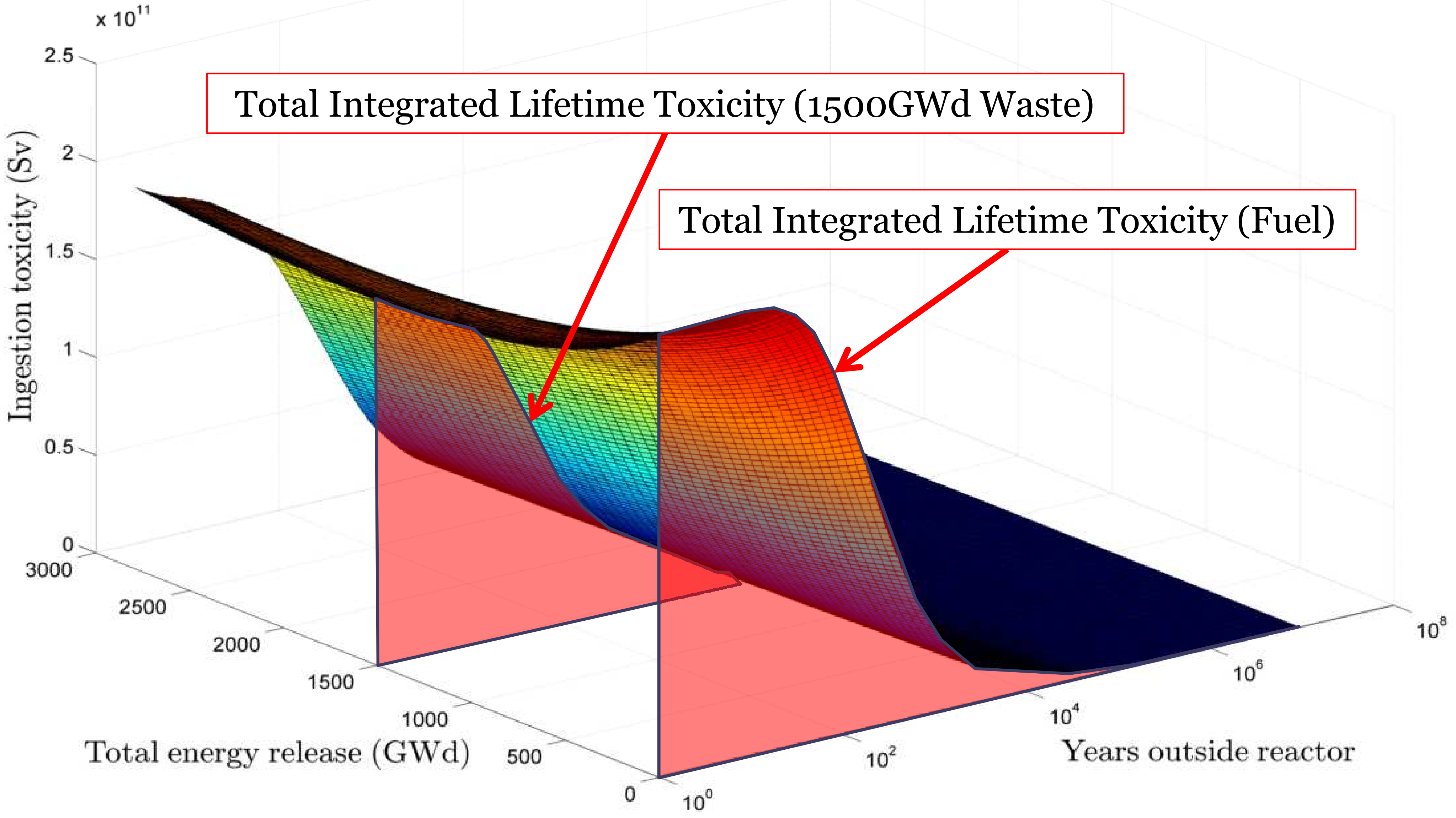


Proliferation Hardness

- Method makes use of Bathke's FOM_1:

$$FOM_1 = 1 - \log_{10}\left(\frac{M}{800} + \frac{Mh}{4500} + \frac{M}{50}\left[\frac{D}{500}\right]^{\frac{1}{\log_{10} 2}} \right)$$

- 100 years of decay modelled
- Critical mass calculated using diffusion method
- Allows "first-glance" assessment of weapon viability
- Metrics:
  - Worst-case FOM_1
  - Maximum reduction in FOM_1

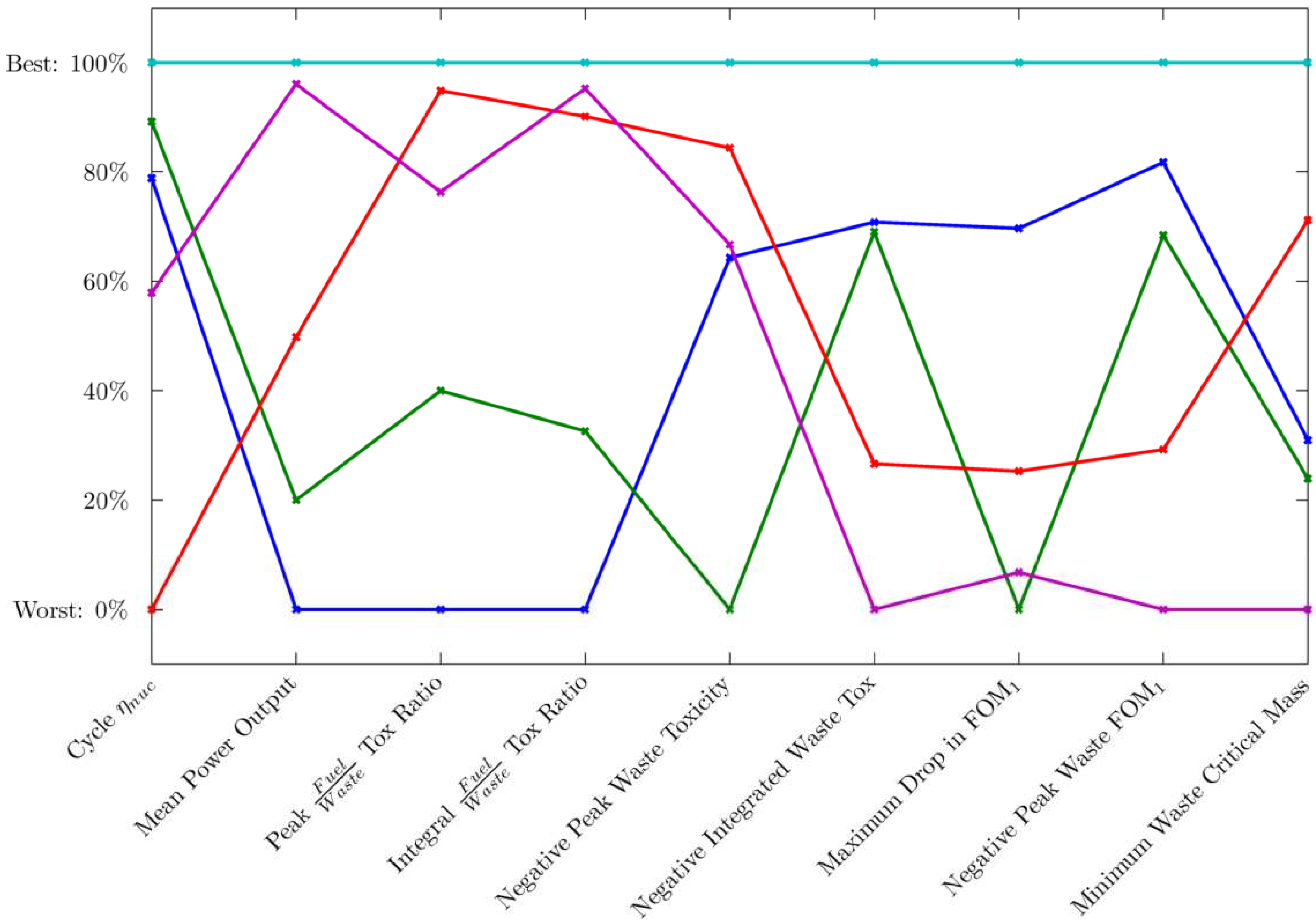
Final Metrics

- Cycle efficiency
- Mean power output
- Ratio of fuel/waste “peak toxicity”
- Ratio of fuel/waste “lifetime toxicity”
- Peak waste toxicity (negative)
- Integrated waste toxicity (negative)
- Maximum reduction in weapon viability
- Peak weapon viability (negative)
- Minimum waste critical mass

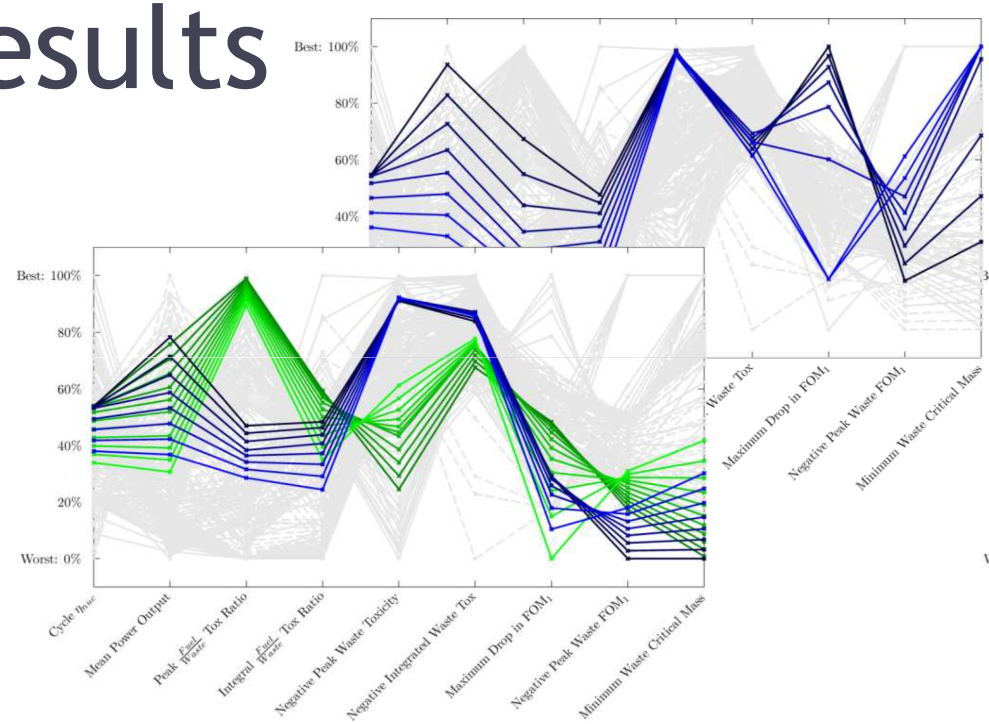
Modelled Cycles

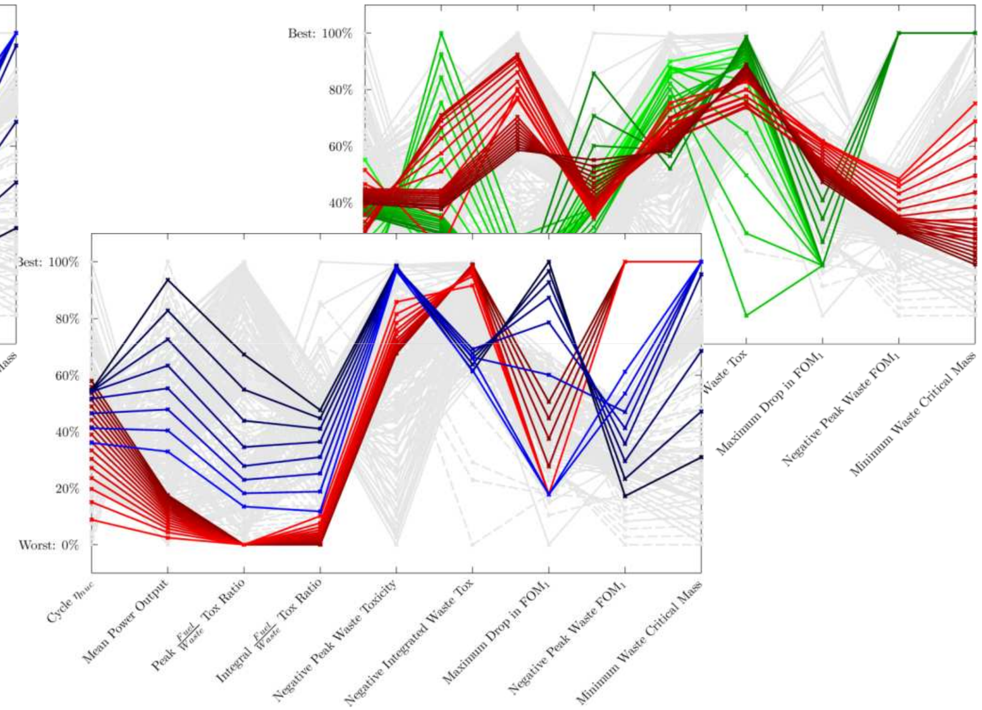
- 4-batch thermal cycles:
  - Enriched uranium (2-10% ^{235}U)
  - Irradiated thorium (2-8% ^{233}U)
  - 5-100% MOx with enriched uranium (3% ^{235}U)
  - 5-100% MOx with irradiated thorium (5% ^{233}U)
- Multi-tier cycles utilising thermal waste
- Fast cycles:
  - Irradiated thorium (6-20% ^{233}U)
  - Superphénix fuel (^{238}U/ ^{232}Th, 10-30% Pu)
- Cycles vetted to ensure reasonable reactivity levels
- Both reprocessed and weapons-grade Pu assessed

Results Formatting



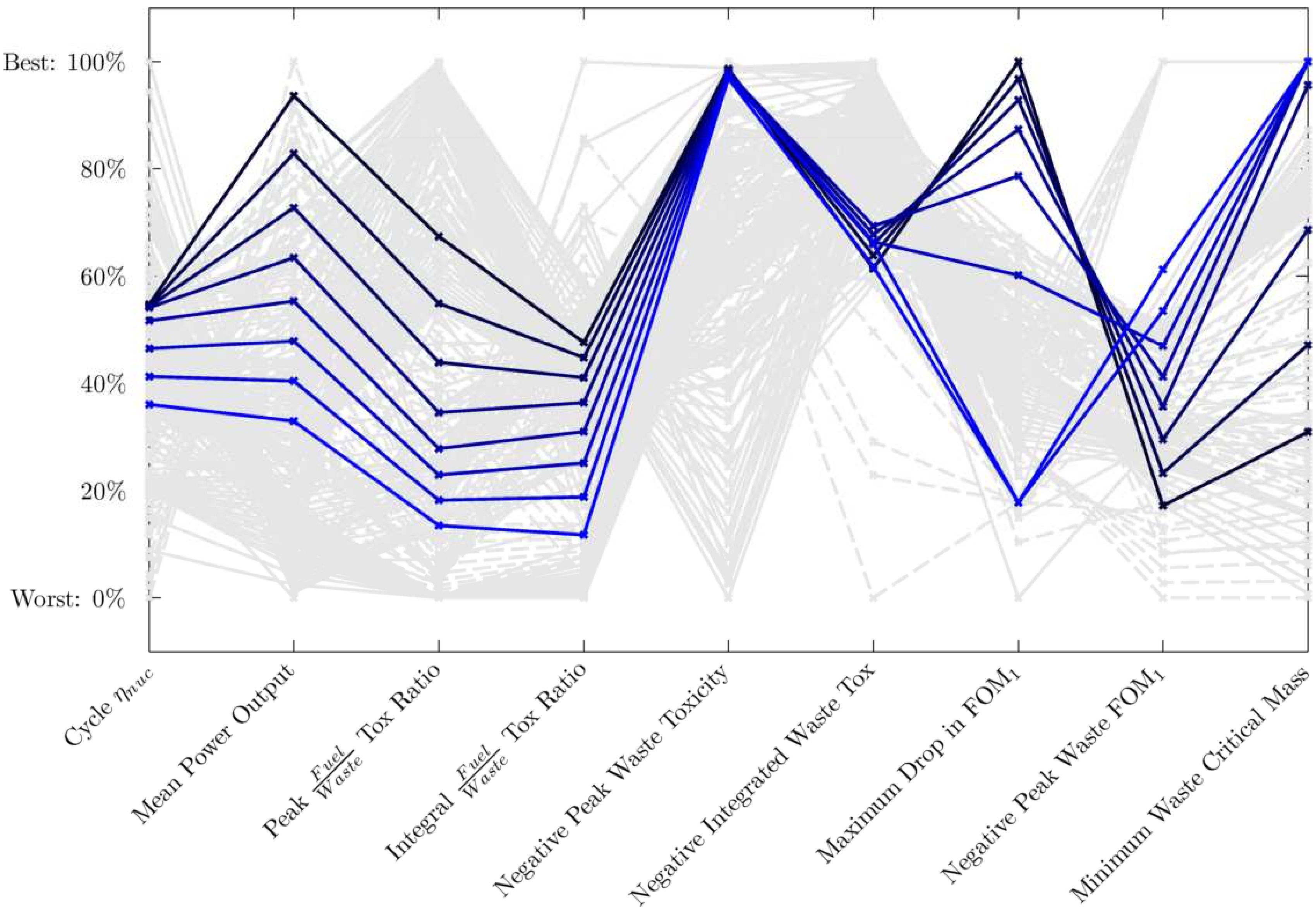
Results





- Cycles can be compared through parallel co-ordinate plots for any or all evaluated metrics
- Some values are truncated, e.g. critical mass
- This allows useful direct comparison between disparate cycles

Thorium Fast Cycles



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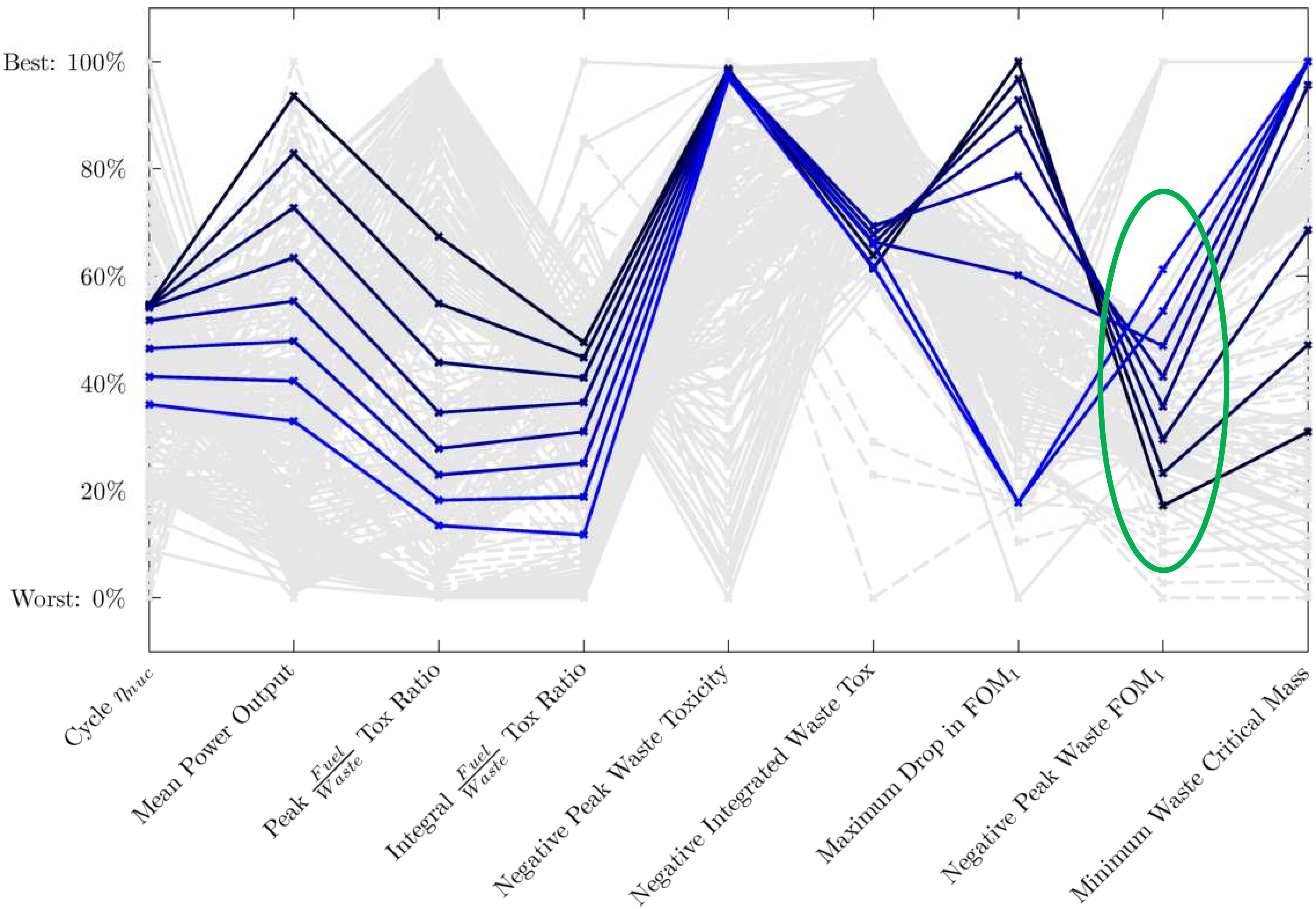

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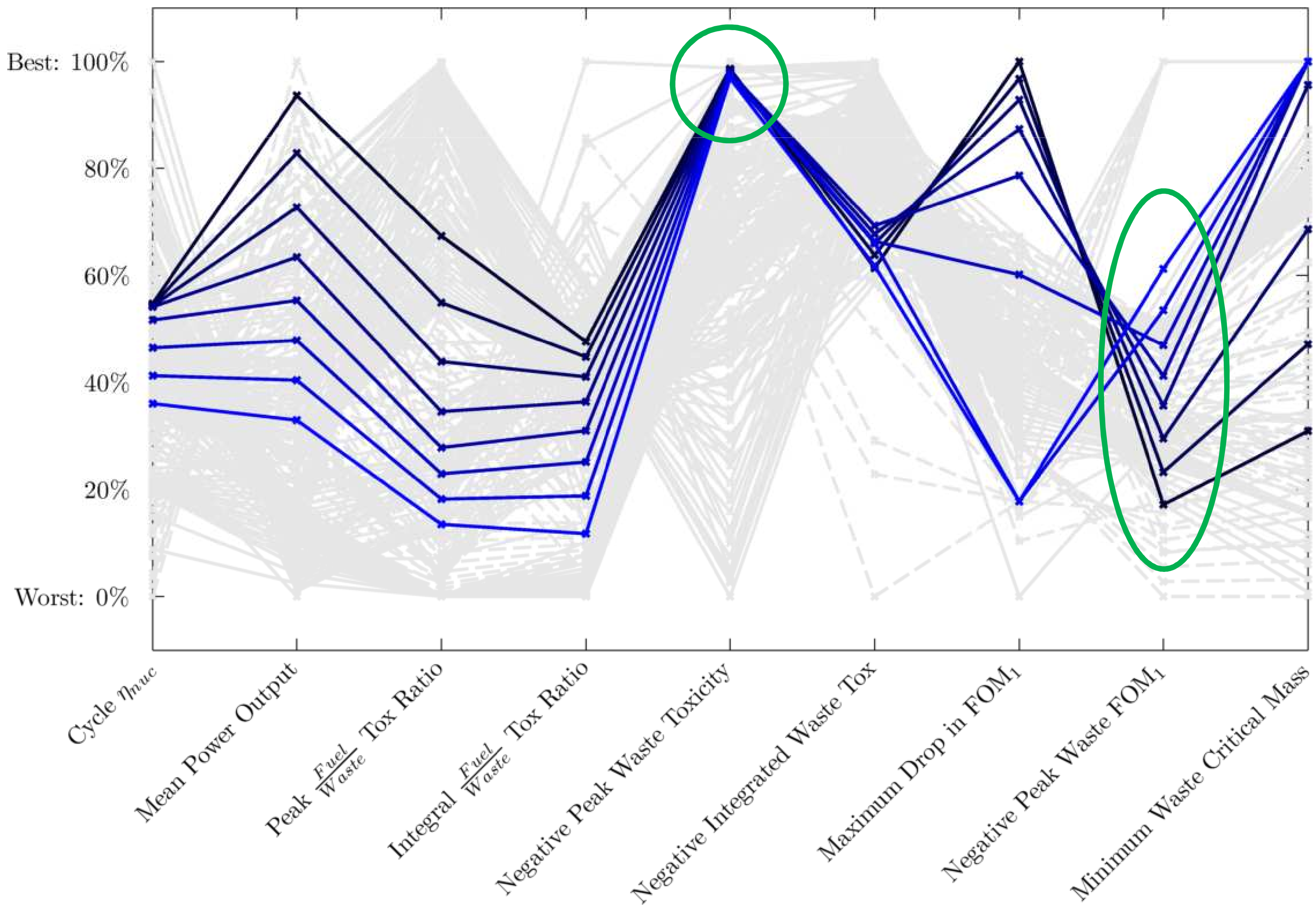
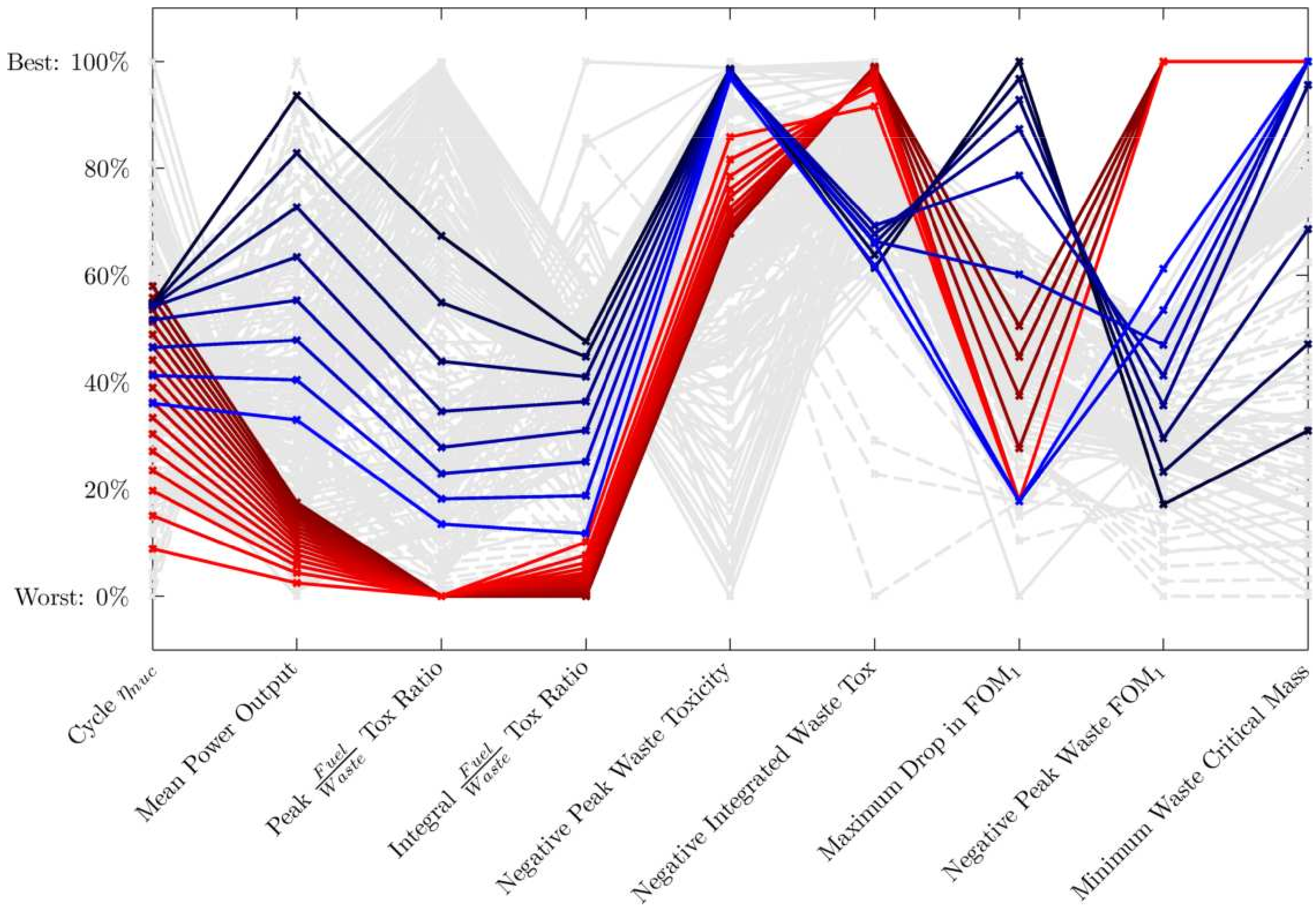


Fast Thorium v. Thermal Uranium



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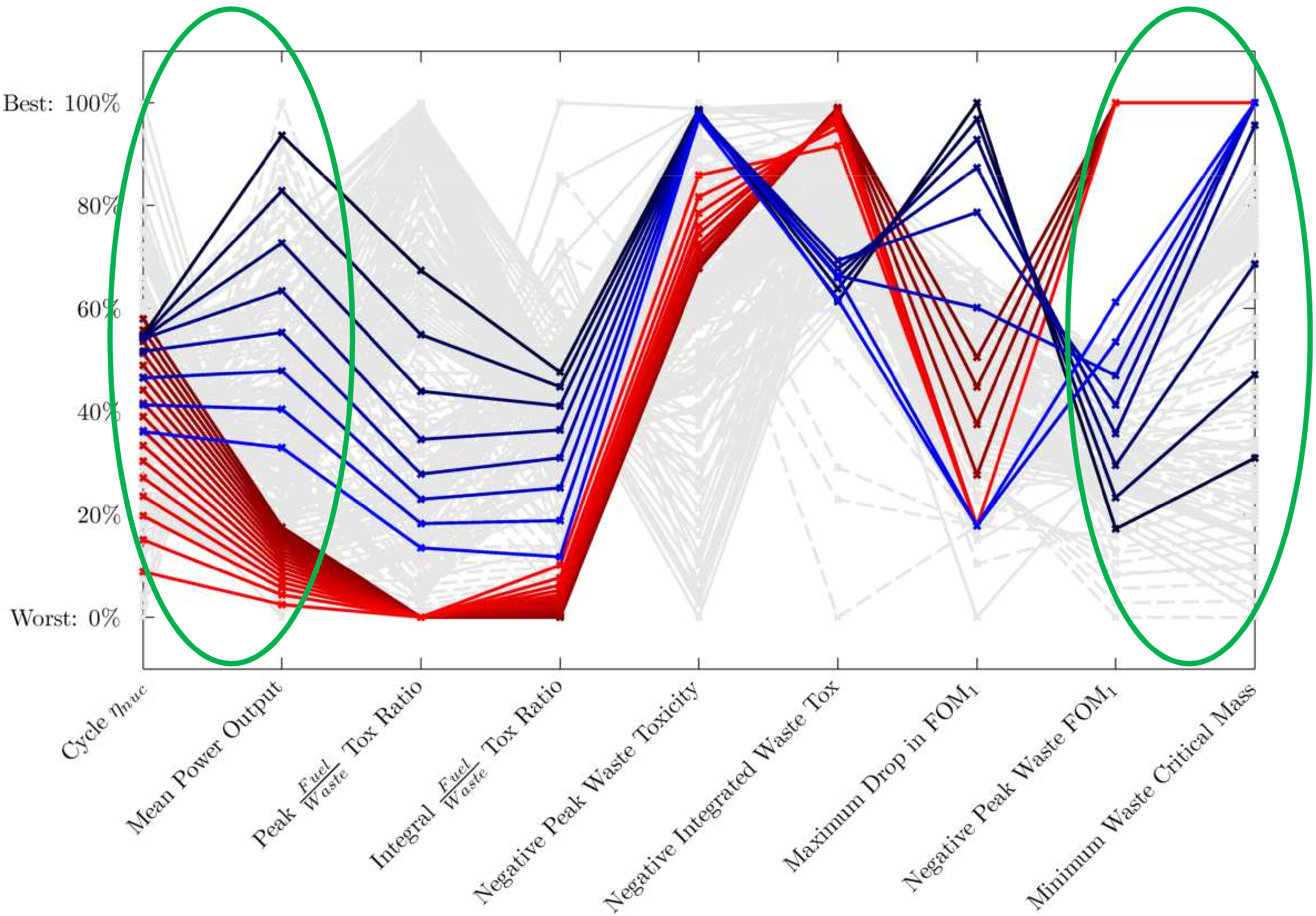
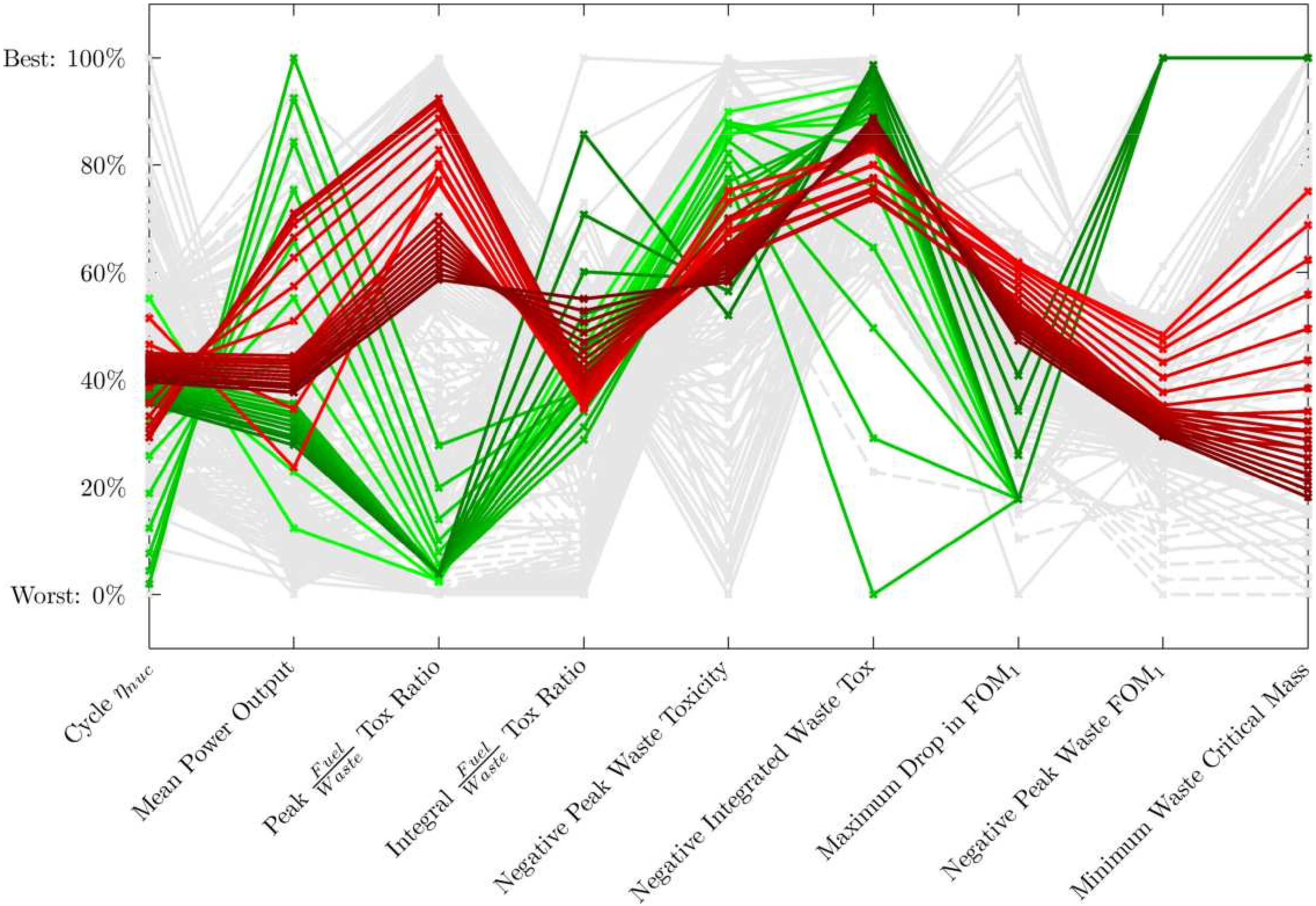


Single v. Multi-Tier



Conclusions I

	Thermal Base								Fast				
	Enriched Uranium	Uranium Multi-Tier	Irradiated Thorium	Thorium Multi-Tier	MOx: Uranium/Pu_D	MOx: Thorium/Pu_D	MOx: Uranium/Pu_W	MOx: Thorium/Pu_W	Irradiated Thorium	Uranium/Pu_D	Thorium/Pu_D	Uranium/Pu_W	Thorium/Pu_W
Efficiency η	Yellow	Yellow	Green	Yellow	Red	Yellow	Red	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow
Power Output	Red	Yellow	Red	Red	Red	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow
Peak Tox. Ratio	Red	Green	Red	Green	Red	Yellow	Red	Yellow	Yellow	Green	Green	Yellow	Yellow
Tox. Burden Ratio	Red	Yellow	Yellow	Yellow	Yellow	Yellow	Red	Green	Yellow	Yellow	Yellow	Yellow	Red
Waste Peak Toxicity	Green	Yellow	Green	Yellow	Yellow	Yellow	Green	Green	Green	Yellow	Yellow	Green	Green
Waste Tox. Burden	Green	Green	Green	Green	Green	Green	Green	Green	Yellow	Yellow	Yellow	Green	Yellow
Drop in FOM_1	Yellow	Yellow	Yellow	Green	Yellow	Yellow	Yellow	Yellow	Green	Yellow	Yellow	Red	Yellow
Waste FOM_1	Green	Red	Green	Yellow	Green	Green	Green	Green	Yellow	Red	Yellow	Red	Yellow
Critical Mass	Green	Red	Green	Yellow	Green	Green	Green	Green	Yellow	Red	Yellow	Red	Yellow

Conclusions II

- No single dominant cycle
- Almost any comparison possible:
  - Reprocessed vs. weapons-grade Pu
  - Uranium vs. Thorium MOx
  - Fast vs. Thermal
- Methodology allows rapid comparison of fuel cycles
- Could be combined with search optimisation methods to produce optimised cycles