Plutonium Recycling via Iterative Mixed-Oxide Fuel Reprocessing

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Research Focus

Plutonium is currently used for nuclear energy production in the form of mixed-oxide (MOX) fuel in a once-through cycle. The spent fuel from these burnup cycles is then discarded as nuclear waste. MOX fuel burnup, however, transmutes uranium into more plutonium which might be usable for additional energy production. One can thus reprocess MOX fuel to extract plutonium for use in new MOX fuel. This process may be repeatable, allowing one to go through multiple such reprocessing iterations.

As plutonium is extracted from spent fuel chemically, reprocessing should not get more difficult throughout recycling iterations. The isotopic composition of plutonium, however, is likely to change as fissile isotopes of plutonium (^{239}Pu and ^{241}Pu) are used up during MOX fuel burnup, while fertile isotopes (^{238}Pu, ^{240}Pu, and ^{242}Pu) accumulate. The question that motivated this study was thus: is such a recycled MOX fuel cycle feasible, and if so, how many times may plutonium be recycled before it becomes unburnable?

Design Goals

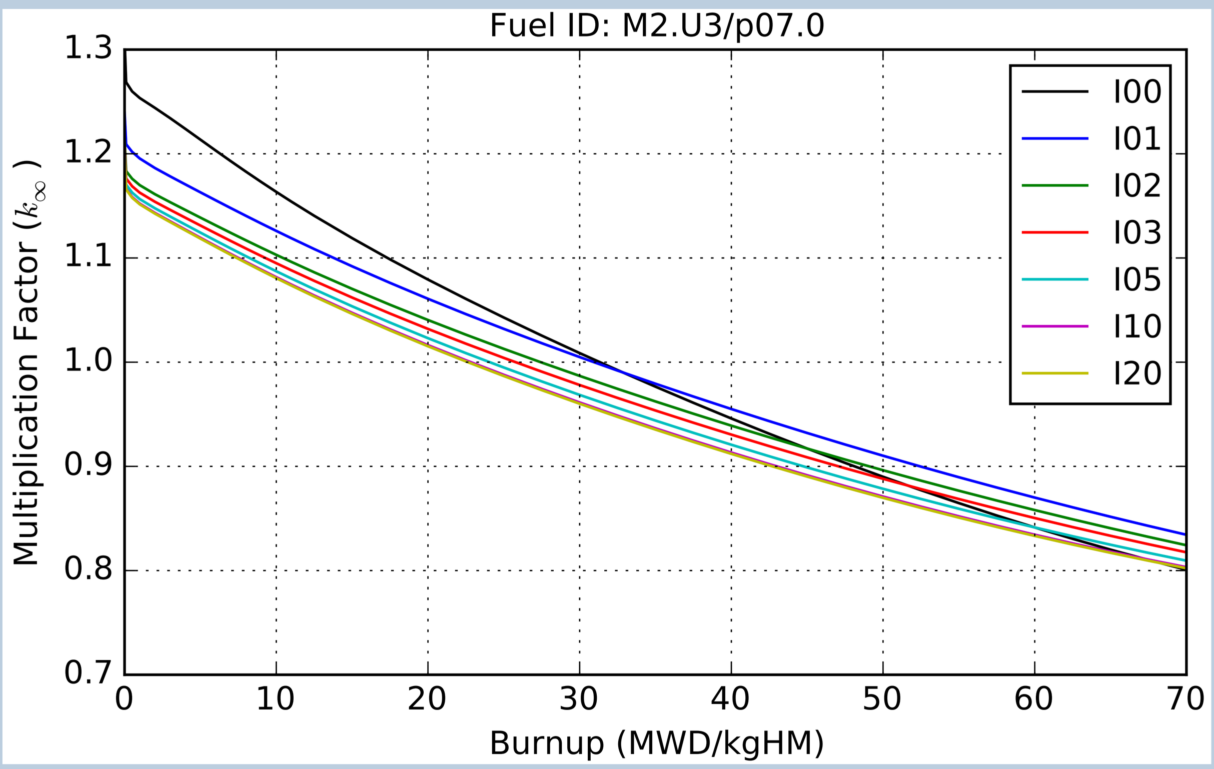
- Parameters such as the ratio of MOX to UO_2 fuel pins in the fuel array, or the plutonium content of MOX fuel pins, can be modulated to find an optimal recycled MOX fuel cycle.
- Sustainability criteria: stable plutonium vector across plutonium recycling iterations, in particular with a burnable proportion of fissile plutonium.
- Compatibility criteria: UO_2 "equivalent" MOX fuel array. Ideally, the MOX fuel properties should be within existing LWR specifications, which puts limits on acceptable MOX fuel properties.
- Reduction of nuclear waste: maximizing the use of plutonium to reduce its contribution to nuclear waste stockpiles, while also making use of depleted uranium, if possible

Methods

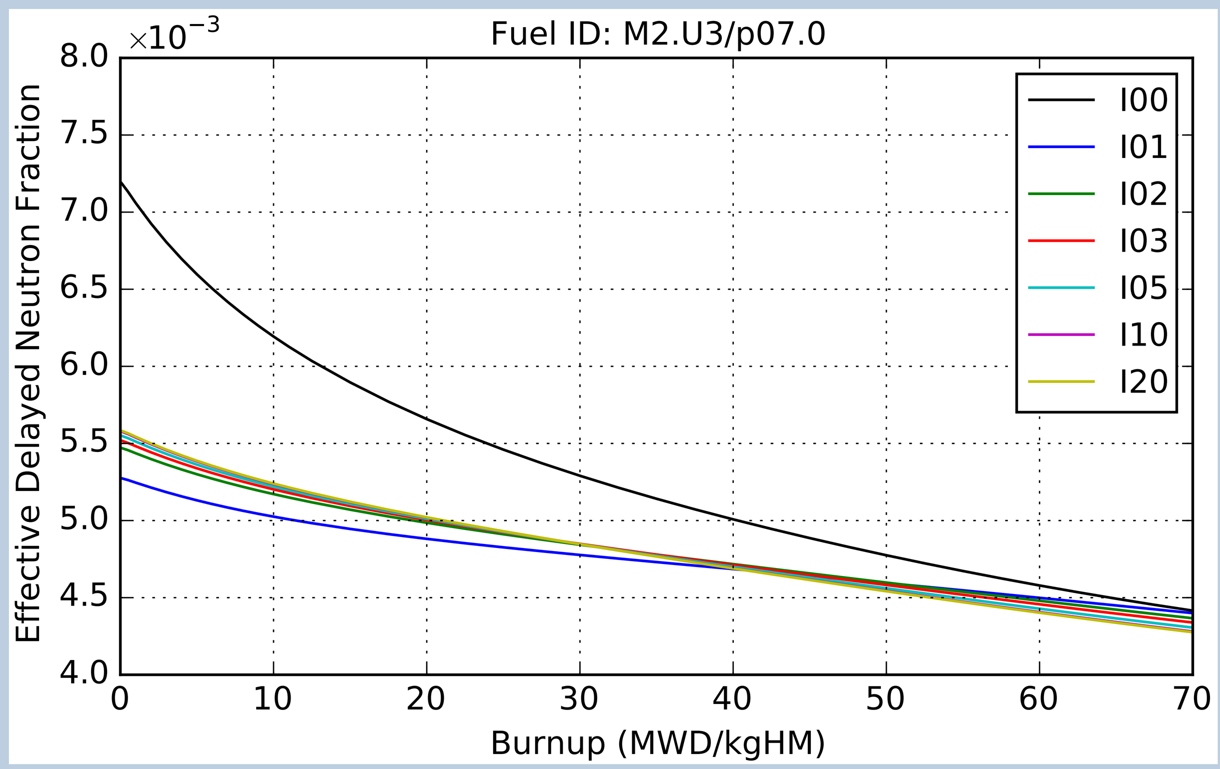
- Recycling algorithm:
  1. Construct initial UO_2 fuel array
  2. Simulate fuel burnup
  3. Extract plutonium vector
  4. Construct MOX fuel array with new plutonium vector
  5. Go to step 2
- Assumptions:
  - No fuel cool-down period between burnup iterations
  - Plutonium extracted from fuel array indiscriminately, making no distinction between UO_2 and MOX fuel pins
  - Plutonium chemically separable to arbitrary purity
- Simulations run using CASMO-4E with the following parameters (in addition to those specified in Simulation Results):

Core average power density	100 kW/liter
Fuel temperature	1000 °C
Moderator temperature	583 °C
Operating pressure	150 bars
Fuel density	10.1 g/cm^3
Boron concentration	800 ppm
Burnup at fuel extraction	50 MWD/kgHM

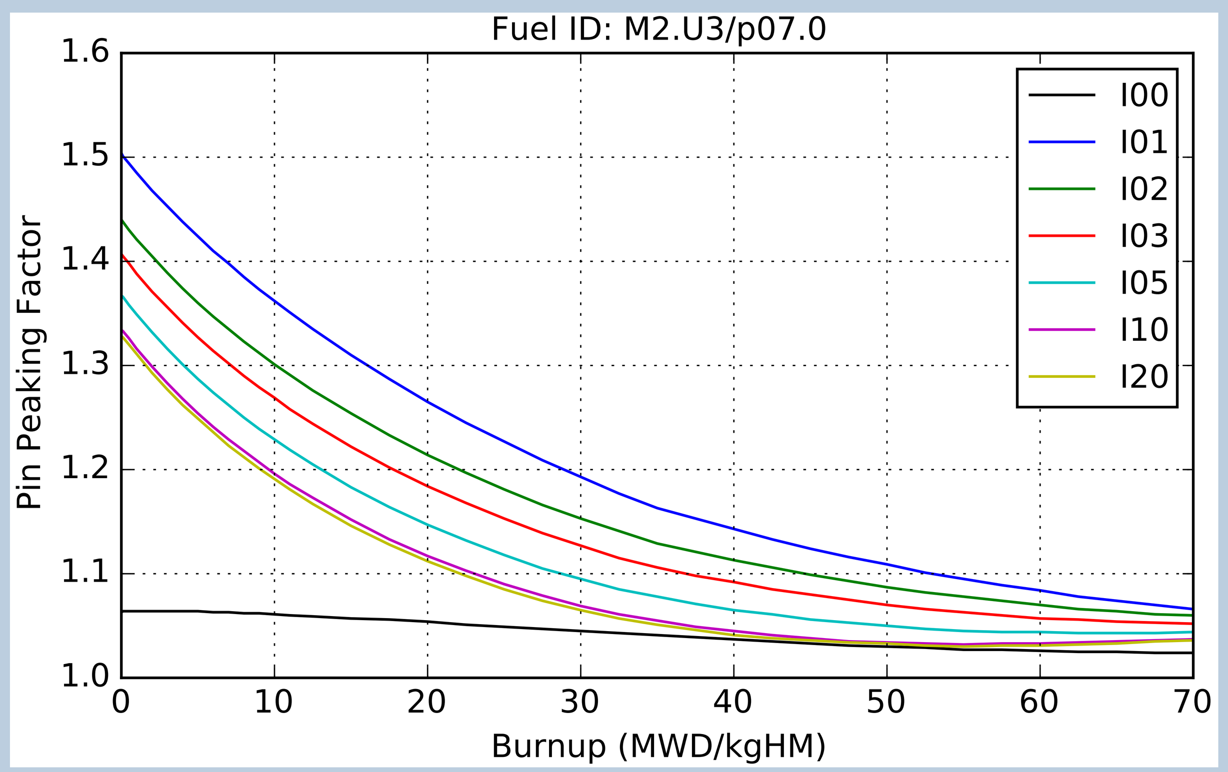
Simulation Results



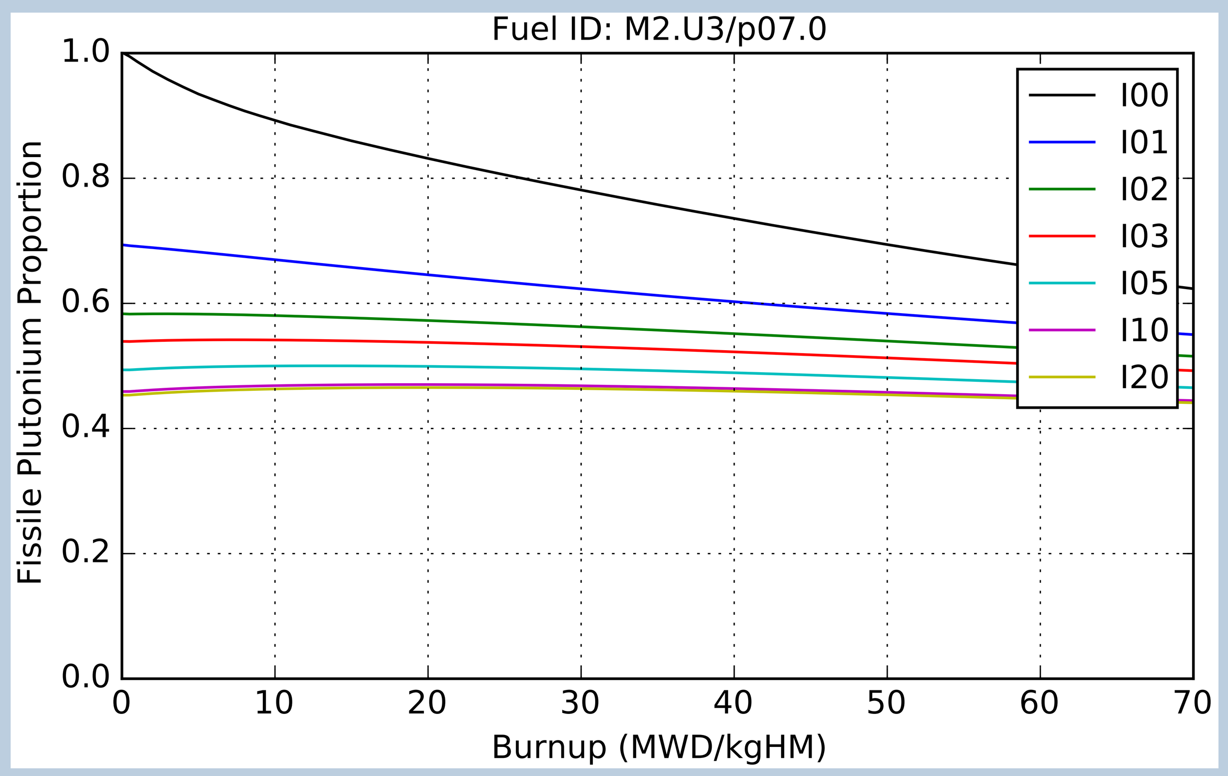
(a) Multiplication factor (k_∞) throughout burnup



(b) Effective delayed neutron fraction throughout burnup



(c) Pin peaking factor throughout burnup



(d) Fissile plutonium proportion throughout burnup

Figure: Fuel properties for multiple MOX fuel iterations throughout burnup according to 2D CASMO-4E simulations of a 17x17 fuel array with 104 MOX and 160 UO_2 pins (~2:3 ratio) in a PWR. UO_2 fuel pins are initially enriched to 4.5% ^{235}U; MOX fuel pins are made using depleted uranium (0.2% ^{235}U) and mixed to 7.0% plutonium. The "zeroth" MOX iteration is a UO_2 only fuel array, and serves two functions, namely to provide i) an initial plutonium vector for the first MOX iteration, and ii) a standard of comparison for the MOX fuel array properties.

Summary and Implications

- Recycled MOX fuel cycle appears to be sustainable
  - Plutonium vector stable and usable throughout burnup cycles
  - Plutonium may be **infinitely recyclable**
- UO_2 "equivalent" MOX fuel array plausibly achievable
- Reduction of nuclear waste
  - Potential **elimination** of plutonium waste
  - Utilization of depleted uranium
- Findings are robust with respect to fuel parameter modulation (e.g. UO_2 to MOX fuel pin ratio, plutonium content of MOX fuel)

Future Work

- Continued burnup data analysis
  - Fuel array parameter space exploration; 3D simulations
  - Reduction and refinement of assumptions
  - Fission product analysis
- Fuel array optimization
  - Establishment of rigorous performance metrics
  - Development of algorithms for acceptable fuel array construction (e.g. minimization algorithms, genetic algorithms)
- Proliferation analysis
  - Plutonium vector design; artificial fuel mixing
- Economic analysis
  - Existing and potential capacity for recycled MOX fuel cycle
  - Current and projected fuel cycle costs; economies of scale

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