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# Comparing the environmental impacts of uranium- and thorium-based fuel cycles with different recycle options

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ABSTRACT

This article addresses the comparative environmental impacts of possible future implementations of several uranium- and thorium-based fuel cycles at steady-state. After carefully defining an appropriate, meaningful, and consistent reference set of fuel cycles for both thorium- and uranium-based options–along with varied extents of recycle–material flow analyses are conducted to determine the mass throughputs in the constituent steps of the fuel cycles. These mass flows are combined with mass-normalized environmental metrics encompassing safety, waste (both low- and high-level) management, and resource sustainability to provide overall perspectives on the environment, health, and safety performance of these fuel cycles. The results indicate that the extent of recycle is generally a more important predictor of environmental metric performance than whether the fuel cycle uses uranium or thorium, although there are still some differences between uranium and thorium for certain metrics. Different fuel cycles perform better with regards to certain metrics, and there is no "best" fuel cycle with regards to environmental impact; the varying relative performance is discussed.



## 1. Introduction

Statements of thorium's performance relative to that of uranium are often made generically, without careful attention to the particular nuclear fuel cycles that are being evaluated. For instance, one might claim that thorium produces "less nuclear waste" than a uranium-based option, but the underlying estimates to support this claim could involve a thorium-based closed cycle in a molten salt reactor compared to the present once-through uranium fuel cycle in pressurized water reactors. If "less waste" is narrowly defined, for example as the volume of spent nuclear fuel (or something similar), then it is possible to present an argument that is "favorable" to the thorium option. However, in the above instance, the conclusion is primarily a property of the extent of recycle rather than the fuel type, and the choice of a single waste metric can also be misleading. A similar example could reach the opposite result if a closed uranium-based fuel cycle and an "open" thorium-based fuel cycle were compared along the same lines.

This analysis considers four representative fuel cycle options that are intended to encompass major categories of possible implementations of fuel type and recycle. To this end, fuel cycles that employ uranium/plutonium and thorium/uranium are considered, including those that employ varying extents of recycle. It is important to consider both dimensions in this study, since comparisons between uranium and thorium are occasionally confounded by inconsistent assumptions regarding the extent of recycle for the different options.

### 1.1. Scope and fuel cycle options considered in study

To arrive at meaningful conclusions, this analysis compares plausible fuel cycle analogues for thorium-based and uranium-based options. It is important to understand that there are inherent, unavoidable limitations in how precisely the two fuel types can be compared. Because thorium contains no naturally-occurring fissile material in the way that uranium does, it requires a fissile input from external sources to "jump-start" a thorium fuel cycle implementation. For fuel cycle options that do not employ either a full or nearly-full fissile material recycle approach, fissile content from external sources will continue to be required even at steady-state. The absence of fissile thorium isotopes also leads to an important difference in supporting fuel cycle facility requirements; natural thorium does not require enrichment

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or conversion[1], although thorium-based fuel cycles may still require those facilities—to the extent that external fissile requirements are supplied by U-235 from mining.

Table 1, below, lists the options that were evaluated in this study. Note that the "no recycle" option is not considered in this study; it is the authors' contention that there is not reactor-based a fuel cycle that can accurately be classified as a "once-through thorium" option[2]. While such labels have been applied in some previous studies, they do not accurately represent the character of the fuel cycle. For instance, in one study the "once-through" system evaluated considers a heterogeneous matrix of uranium-based driver fuel and thorium-based blanket fuel that is configured to be taken to high burnups without subsequent fuel reprocessing. The work supporting the evaluation of this "once-through" option is extensive, spanning several years and incorporating an optimization component (Galperin et al., 1999; Todosow and Kazimi, 2004). However, thorium only comprises about 2% of the total natural resource requirements of the system while natural uranium comprises the other 98% (SNL, 2016); thus, the system is better described as a uranium-based fuel cycle with minor amounts of thorium added for specific functional enhancements. As this study will show, modified-open recycle systems will generally also use more uranium than thorium, but at least in the case evaluated in this study, the balance is not nearly so lopsided as for the "once-through" thorium option and thorium plays a central role to the fuel cycle studied.

For reference, U-233 is Th-232's fissile counterpart, and is produced by a neutron capture and two subsequent beta decays; thus, the relationship between Th-232 and U-233 is similar to that of U-238 and Pu-239. The reference fuel cycles included in this study are intended to be roughly representative of major groups of fuel cycle options, based on fuel type and recycle strategy. There are other potential variations of these fuel cycles that could be considered based on different reference technologies, material stream separation assumptions, etc.; however, these were selected based on their relative technical maturity and, for the full recycle systems, the fact that these are technologies are frequently mentioned by advocates for these fuel cycles. Thus, it is important to recall that this paper represents a high-level introduction to how the impacts associated with future implementations of nuclear fuel cycles might differ between representative and comparable options. Some of the results are sensitive to the input assumptions and uncertainties therein, and different assumptions could lead to different results. Each of the options summarized in Table 1 is described further below.

*The reference modified-open, uranium-plutonium fuel cycle (MUPu)* is a two-stage system involving two pressurized water reactors. The term "stage" in this context refers to a specific reactor-fuel combination in addition to its supporting front-end (e.g., resource recovery, conversion/enrichment, fuel fabrication) and back-end (e.g., reprocessing, disposal) fuel cycle steps and facilities; this "stage" terminology is adopted from the US Department of Energy (DOE), Office of Nuclear Energy's Fuel Cycle Option Evaluation and Screening Effort (FCO-ESS) (Wigeland et al., 2014). A stage may receive nuclear materials from another stage and send nuclear materials to another stage. The first stage is a "conventional" PWR fueled by uranium dioxide, where natural uranium is enriched to 4.21% U-235 and fabricated into fuel. The uranium dioxide fuel is irradiated to a burnup of 50 GWd/MT and then stored for a fixed period. After this interim storage period, the fuel is sent to reprocessing, where all the plutonium and some of the uranium are recovered to be fabricated into uranium-plutonium MOX fuel for the second stage. The excess uranium (i.e., that which is not required to fabricate MOX fuel), the minor actinides, the fission products, and any process losses may become constituents of high-level waste[4]. The MOX fuel is also irradiated to a burnup of 50 GWd/MT in the Stage 2 PWR, and the spent fuel will be sent to disposal (without reprocessing following interim storage). Both PWRs are assumed to have a thermal efficiency of 33.33%. The material flow and component steps of this fuel cycle are shown in Fig. 1. Only initial-heavy-metal and heavy-metal-derived (i.e., fission products) material flows are shown. Material streams in bold italics are those that must be managed as high-level waste streams, i.e., will require further storage and eventual geologic disposal.

*The reference modified-open thorium/uranium-233 fuel cycle (MThU)* is a two-stage system with a single recycle of U-233 between the stages. Fig. 2 shows the major material flows of this fuel cycle. Note that this study assumes that natural thorium will be recovered as a by-product of titanium mining, which is the recovery approach that is currently practiced, offers economic and environmental benefits compared to directly "mining" for thorium, and has been shown to viable for the indefinite future (Ault et al., 2016b). The use of by-product thorium has been embraced by recent systems studies conducted by both the Organisation for Economic Co-operation and Development's (OECD's) Nuclear Energy Agency (NEA (2015) and the FCO-ESS (Wigeland et al., 2014).

The combined (driver and blanket) Stage 1 burnup is 61.8 GWd/MT (26.5% driver fuel by mass, 73.5% blanket fuel by mass), while the Stage 2 burnup is 56.0 GWd/MT. Both PWRs have a thermal efficiency of 33.33%. The enrichment of the Stage 1 driver fuel is 12.2%. The Stage 1 parameters are derived and/or adapted from a design described in a previous analysis documented in the Fuel Cycle Option Catalog (SNL, 2016). The design is made viable by the fact that reactivity is essentially "transferred" from the enriched uranium driver fuel as U-233 accumulates in the thorium blanket fuel. This means that the decline in overall reactivity over time is relatively slow.

The MThU fuel cycle is intended to be a close analogue to the MUPu fuel cycle, in order to make direct comparisons defensible. That being said, there are some important (and unavoidable) differences between the two fuel cycles. The most important difference is that external fissile material (U-235 from enriched natural uranium) is used to breed the supply of U-233 in Stage 1 to be used later in Stage 2, because thorium does not contain fissile material. Either relatively high enrichments[5] or a significant uranium fuel fraction (or both) is necessary in Stage 1 to sustain criticality and to breed appreciable quantities of U-233 in thorium blanket fuel (Galperin et al., 1999). The consequences of relying on enriched uranium are that (1) the front-end facilities associated with enriched uranium (U mining, conversion, enrichment, and de-

[1] Uranium conversion achieves two major objectives: moving the uranium into a fluoride chemical form to facilitate subsequent enrichment and purifying the uranium to nuclear-grade impurity levels. While the fluoride chemical form is not required for thorium, the purification step is still required, and is generally rolled into a step called "refining" for thorium.

[2] Externally-driven systems such as accelerators may enable once-through thorium options; see (Brown et al., 2016).

[3] The definition of "closed" used in this table does not include the recycle of minor actinides.

[4] However, it is plausible that recycled uranium would be eligible for separate, less stringent disposal classification and requirements compared to those of "primary" HLW categories; studies have been dedicated to the management of reprocessed uranium (e.g., (IAEA, 2007)).

[5] Further, it is recognized that the enrichment assumed in this study is a higher enrichment that presently used, or authorized (NRC, 1986) in current LWRs, such enrichment levels have been manufactured in the past (e.g., Brey, 1979) and are presently in limited use (e.g., the PR-2 reactor used for materials testing and medical isotope production in Belgium (Koonen, 2009)).