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# Middle-term thorium strategy for PWR fleets

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ABSTRACT

Thorium constitutes a natural resource alternative to uranium to fuel nuclear fission power plants. This study explores an original way to benefit from thorium with pressurized water reactors (PWR). It relies on a versatile reactor EPR™ core concept which well circumscribes thorium fuel reprocessing and re-fabrication

Fleets representative of what can be deployed at the scale of a small country were simulated using the scenario software COSI6. The cornerstone of this study is here the possibility to multi-recycle plutonium into Pu/Th fuel as plutonium degradation is softened by mixing it with high-grade fissile matters. Plutonium content inside Pu/Th fuel remains then far below the limit existing in PWR for safety reasons. This synergistic effect between U/Pu and U/Th cycles enables a better valorization of fissile elements present in spent fuels.

Improved plutonium management makes possible to stabilize spent fuel stocks and the plutonium inventory at the cycle back-end. Thanks to multi-recycling allowed by the U/Pu/Th studied scheme, uranium resource savings exceed 25%. Minor actinides production is also reduced even though production of curium alone increases. These results reveal that thorium introduction in standard PWR may be a sustainable middle-term option, assuming that U/Pu/Th fuel reprocessing and re-fabrication would become available.

## 1. Introduction

There are basically three ways to use thorium in civil electronuclear systems. In near future (typically before 2030), it might be introduced in small quantities (5–10%) in existing nuclear reactors as an oxide fuel additive to improve core power flattening and neutronics. It may also allow to reduce burnable poisons such as gadolinium (NEA, 2014), since $^{232}$Th captures around twice more than $^{238}$U. Long-term thorium deployment strategies (after 2050) consist in building up a reactor fleet ultimately relying on a closed fuel cycle: new reactor concepts (Heuer et al., 2014; Schaffer, 2013) are then to develop to optimize the thorium conversion and the use of $^{233}$U as a fissile element, as in the three-stage development program currently supported by India (Rodriguez and Bhoje, 1998). In particular, high-temperature gas-cooled reactors (HTGR) are being studied as they constitute interesting innovative GEN-IV concepts (Cerullo and Lomonaco, 2012) for advanced Pu/Th cycles (Mazzini et al., 2008), which may target waste reduction (Cerullo et al., 2015; Bomboni et al., 2008). Thorium resources are indeed abundant enough for a long-term and sustainable development of thorium-based cycles (Warren and De Simone, 2014). In the gap (2030–2050), thorium may be used to save uranium resources, improve spent fuel management and/or plutonium recyclability (Energy Policy Editorial, 2014). It could become particularly attractive if uranium resource is rarefying whereas fast reactor deployment remains limited for this period.

Medium term thorium options should lie in conservative assumptions with respect to technological breakthroughs and new facilities at industrial scale. Thorium/uranium/plutonium reprocessing is still under development (Patak et al., 2003; Shatalov et al., 2001) and may require hot cells shielded with over 40 cm of leadglass (Leniau, 2013) since $^{208}$Tl, a decay product of $^{232}$U extracted with $^{233}$U, is a 2.6 MeV $\gamma$ emitter. Since heterogeneous cores make possible specific reprocessing chains dedicated to thorium spent fuels, thorium fuel may be loaded in-pile with heterogeneity at the level of the fuel assembly (NEA, 2014). The capacity of the thorium fuel reprocessing facility could therefore remain reasonably low. Besides, before 2050, thorium should be introduced in existing reactors such as generation III pressurized water reactors (PWR) initially developed for the U/Pu fuel cycle, with only minor changes brought to expand their fuel acceptance.

Thorium is a fertile element, thus PWR thorium fuel must contain a fissile material, low-enriched uranium (LEU) or plutonium from LEU reprocessing in a first stage. If some LEU is incorporated into a thorium matrix, its enrichment has to remain below 20 wt% to abide by the international non-proliferation treaties. Practically, its enrichment should be close to 20 wt% so that the thorium content would remain as high as possible in the U/Th fuel. In this case, it should be necessary to feed the cycle with significantly larger amounts of natural uranium (NatU) and separative work units than for the standard

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uranium cycle for a same energy output (NEA, 2014). At the opposite, Pu/Th fuel does not need isotopic enrichment and may be deployed relatively rapidly since it possesses similar neutronic properties than the well-established MOX fuel (Insulander and Fhager, 2009). In this study, thorium is therefore introduced in the core of European pressurized water reactors (EPR™) by means of heterogeneous assemblies, each composed of a LEU seed and a Pu/Th fuel ring.

In the 2030–2050 period, Pu/Th fuel reprocessing is assumed to occur at the scale of a pilot plant of limited capacity. Thus, although $^{233}$U-rich uranium might be recycled into LEU to save the most possible natural uranium and enrichment energy (Vallet, 2012), it is used here in the re-fabrication of new Pu/Th rings. This way to proceed circumscribes hot cell reprocessing and re-fabrication steps to the single Pu/Th fuel. It moreover makes plutonium multi-recycling particularly viable (see part 3.1). The synergy between U/Pu and U/Th cycles therefore carries substantial results in terms of resource savings concomitantly with better spent fuel and plutonium management essentially. These results are highlighted by comparing scenarios which simulate small fleets of 8 EPR™ with various fuel loading schemes.

## 2. Simulation

### 2.1. Reactors

The concept of EPR™ core with thorium developed by AREVA and LightBridge (AREVA, 2010) is constituted of 17 × 17 hybrid assemblies: the seed contains LEU enriched to 4.9% and the two peripheral raws a (Th,Pu)OX fuel with initially 8% Pu (for a plutonium typical of the stock available in France in 2035). Fig. 1 shows a scheme of such an assembly with guide rods visible in the seed part. In the reactor core, the fuel contained into Pu/Th rings weights approximately 50 tons (heavy metal): it represents around 45% of the total fuel mass. This core concept offers a relatively poor conversion ratio of thorium since the EPR™ operates in a thermal neutron spectrum optimized for the U/Pu cycle (Ernoult, 2014). However thorium addition is generally favorable to Pu incineration. This is the case in light water reactors (LWR) (Weaver and Herring, 2003), so the use of thorium as a vector for Pu multi-recycling actually makes sense (see Section 3.1).

As current French PWR, EPR™ can also be fueled with 100% LEU or with MOX fuel (from 30% to 100% (Tiphine et al., 2015)). EPR™ is in this respect a versatile reactor compatible with advanced fuel cycles (Vezzoni et al., 2009; Martin et al., 2016). LEU is then enriched to 4.2%. MOX refers to a (U,Pu) oxide fuel made with depleted uranium from LEU enrichment and plutonium from used LEU reprocessing (as currently done in France). A constant 0.83 load factor is assumed for EPR™ and its nominal power is nearly 1.53 GWe regardless of its loading. Fuel core management is carried out by thirds. All the fuels are irradiated during 3 cycles of 517 equivalent full power days, at the end of which Pu/Th rods reach a burnup of 61 GWd/t.

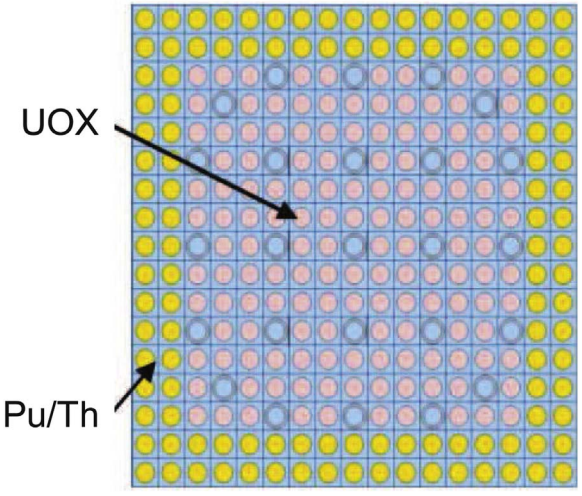


**Fig. 1.** Scheme of the 17 × 17 assembly with a Pu/Th ring of 2 raws designed for EPR™ (AREVA, 2010).

### 2.2. Fuel cycle

MOX fuel batches are stored after irradiation since their recycling in PWR would require plutonium contents in new fuels higher than the current safety limits (Martin et al., 2016). In this respect, fast neutron reactors shall be used in France to absorb used MOX fuels first and foremost. LEU and Pu/Th fuel reprocessing are here supposed to occur in distinct facilities. The LEU reprocessing plant is here similar to La Hague, except that its capacity is lower. The Pu/Th reprocessing plant is assumed to separate uranium, plutonium and thorium with 99.9% efficiency. Pu/Th is recycled following these steps:

1. The $^{233}$U-rich uranium from spent Pu/Th rings (RepU) is used to supply the new Pu/Th fuel.
2. The plutonium from spent rings is then added in the new rings as a supplementary fissile material.
3. If the new Pu/Th fuel still lack fissile atoms, some high-grade plutonium from LEU reprocessing is then withdrawn.
4. The remaining part of the new rings is then completed with fertile thorium. Th coming from Pu/Th reprocessing is first consumed.
5. Some natural thorium is eventually provided to complete the Pu/Th fuel fabrication.

For sake of clarity, Fig. 2 illustrates the fuel cycle of the scenario Pu/Th-MOX (see part 2.3). It must be highlighted that the feasibility of the scenarios is conditioned by major assumptions, which include the industrialization of the thorium fuel recycling and re-fabrication processes. Thorium fuel fabrication should not constitute a major issue since some Pu/Th fuel has already been made (Insulander et al., 2013, 2015) and the building of a pilot manufacturing line was even initiated in Brazil (U/Th fuel) (Fortini et al., 2015). Besides, separate extraction of uranium, plutonium and thorium is now possible at the lab scale (NEA, 2014), but thorium fuels remain particularly hard to dissolve (use of hydrofluoric acid in the nitric solution). At last, thorium fuel re-fabrication may also constitute a challenge regarding radiation protection.

All the irradiated fuel batches are cooled at least 5 years before their transport and reprocessing. This period is probably not best suited for Pu/Th fuels. However, although the cooling time of thorium fuels impacts the kinetics at which the scenarios evolve, it should not affect the results when a steady-state is reached. In the same way, fabrication always lasts 2 years whatever the fuel type and composition, including prior reprocessing if any.

### 2.3. Scenarios

5 scenarios of 8 EPR™ were simulated, possibly representative of small reactor fleets of 12.2 GWe at the scale of a region or a little country. They deliver the same power (90 TWhe/yr), which facilitates their direct comparison. The COSI6 simulation code (Coquelet-Pascal et al., 2015) was used. It relies on the CESAR5.3 code and JEFF-3.1.1 nuclear data library (Vidal et al., 2012), and remains a reference in the domain of electronuclear scenarios.

The 8 EPR™ are fueled with LEU only when they start at $t_0$, since there is no plutonium to make any MOX or Pu/Th fuel at this stage. LEU is then irradiated for *circa* 5 years, and stored for cooling during at least 5 additional years before reprocessing. Accounting for 2 more years of fuel fabrication, 12 years elapse between $t_0$ and the introduction of first MOX or Pu/Th fuels in-pile. In the same way, the matters from Pu/Th reprocessing are recycled into new Pu/Th rings after 12