A View on the Thorium Fuel Cycle

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Abstract

The thorium fuel cycle is analyzed in relation to the advantages demonstrated and expected, and of the known disadvantages. The need for R&D is described in order to get definite answers on the economics of the fuel cycle, the viability of Thorex reprocessing, and the proliferation issues. The time to build up a fleet of Th reactors is simulated for typical scenarios of installed capacity.

Background

The thorium fuel cycle is based on the transformation of naturally occurring Th-232, which is fertile, into fissile U-233 by neutron capture [see (1)]. Thorium is therefore not a nuclear fuel and the neutron capture needed to generate U-233 is an expensive initial investment. U-233 has a very favourable fission to capture ratio, superior to U-235, Pu-239 or Pu-241. In a thermal neutron spectrum, the fission to capture ratio is favourable enough to allow a breeding cycle, which is not possible with any other fissile nuclide. The Th-232/U-233 fuel cycle has been considered attractive, because it offered the prospect of a breeder or near breeder in a thermal reactor, with fewer technical obstacles than were posed by fast reactors. Early efforts to establish the thorium fuel cycle included a demonstration in the thermal breeder programme in the Shippingport PWR. This was designed to demonstrate a breeding ratio close to 1.0 and in this respect it was successful. But it is unlikely that this fuel cycle would be economic under current conditions. U-233 can also be fissioned in a fast neutron spectrum, in the same way as other fissile nuclides. However, it is disadvantaged compared with Pu-239 with a smaller number of neutrons per fission.

$$\text{Th-232}\ (\text{n},\gamma) \rightarrow \text{Th-233}\ (\beta^-) \rightarrow \text{Pa-233}\ (\beta^-) \rightarrow \text{U-233} \tag{1}$$

The thorium fuel cycle can be deployed in a once-through fuel cycle or with recycle. The once-through fuel cycle is simpler technologically, but only offers very limited benefits in terms of uranium utilisation. Full recycle with Th-232/U-233 offers an unlimited resource, but also poses many technological challenges, especially reprocessing and fuel manufacture.

Pros and Cons

The Th-232/U-233 has often been claimed to have advantages over the U-Pu fuel cycle, some of which are justified and some are not:

- *Sustainability*: Th-232 is without doubt more abundant than uranium and if a market developed it would represent an enormous energy resource. The fact that no enrichment is required is also helpful, as it reduces the mining requirement by a factor of about 10 compared with current LWRs. If the Th-232/U-233 cycle could be

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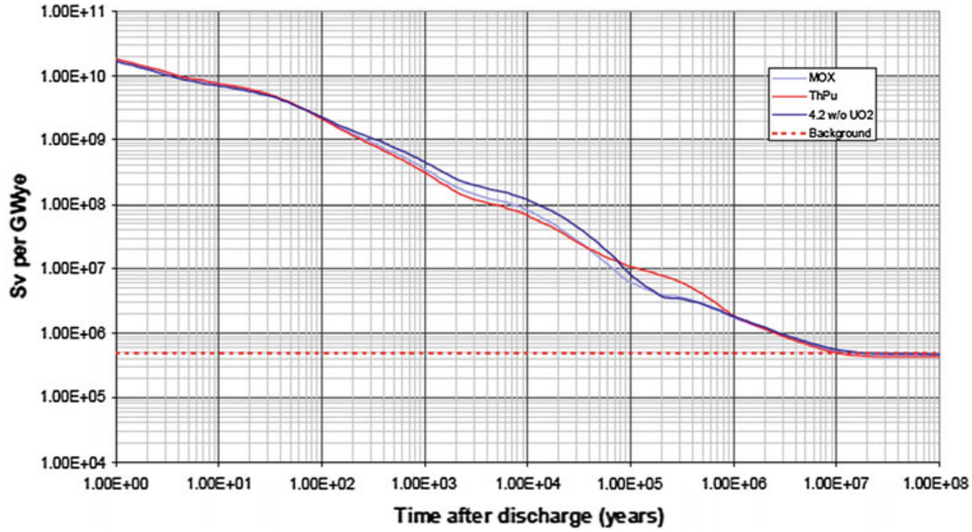
Fig. 1 Radiotoxicity over time for a range of fuel types



taken to equilibrium with recycle, it would represent an unlimited resource. Once-through thorium fuel cycles only give a marginal improvement in sustainability.

- *Neutrons per fission*: favourable in a thermal spectrum, but unfavourable in a fast spectrum as noted above.
- *Waste inventories*: The fission products produced from U-233 fissions are essentially the same as those from the U-Pu fuel cycle. The much reduced transuranic inventory is not necessarily advantageous in a repository, where transuranic transport to the environment is not the controlling factor for dose rates to the limiting groups. Considerable R&D would be needed to establish the waste forms that will arise from a full recycle scheme with Th-232/U-233.
- *Radiotoxicity*: Because the thorium fuel cycle starts at an atomic mass of 232, it takes many more neutron captures to generate transuranics such as Np, Pu, Am and Cm. Once fission products have decayed after about 500 years, the radiotoxicity of the U-Pu fuel cycle is dominated by transuranic elements and the Th-232/U-233 fuel cycle has a much lower radiotoxicity. However, in the very long term Th-232/U-233 systems always have a higher radiotoxicity than their U-Pu equivalents because of the build-up of daughter nuclides from the U-233 decay chain. The radiotoxicity of the thorium fuel cycle therefore depends on the timescale in question and is not always favourable. Figure 1 illustrates how radiotoxicity varies for selected U and U-Pu (MOX) fuels and Th-Pu fuel.
- *Fuel properties*: ThO has some advantages over UO_2 as a fuel matrix, with higher thermal and chemical stability. ThO additives to UO_2 fuels are being developed currently, with irradiation testing already under way. The benefits are likely to be worthwhile, but nevertheless incremental improvements on current UO_2 fuel technology.
- *Reprocessing*: The reprocessing of thorium fuel is less straightforward than with the uranium–plutonium fuel cycle. The recovery and purification of U-233 from neutron irradiated Th reactor fuels through Th extraction (the Thorex process) has been demonstrated on a small scale, but will require R&D to develop it to commercial readiness.
- *Inherent proliferation resistance*: It is often stated that U-233 is inherently proliferation resistant, but this is questionable. U-233 has very favourable properties for nuclear weapons, either as part of state sponsored proliferation or for an improvised nuclear device (IND). The presence of U-232 at hundred ppm levels is claimed to protect against its use in an IND, but the fact is that the protective radiation field from the U-232 is insufficient to cause rapid incapacitation and therefore only a partial barrier to an IND. Overall, the industry assesses the thorium fuel cycle as posing a comparable proliferation threat to that posed by the U-Pu fuel cycle.
- *Economics*: It is sometime stated that the thorium fuel can be more economic than the U-Pu fuel cycle. But this does not account for the fact that a thorium fuel cycle would require the development and deployment of a new infrastructure in competition with the existing U-Pu infrastructure. At present, there is insufficient understanding at the detail needed to judge whether the thorium fuel cycle would be more economic in practice.
- *Plutonium disposition*: ThO fuel theoretically offers a more stable matrix for plutonium disposition, with the advantage of avoiding the production of new Pu-239 from U-238 captures.

- *Void coefficient mitigation*: Thorium fuels drive the void coefficient toward more negative values in thermal systems. In light water reactors (LWRs), a positive void coefficient is usually considered unacceptable and limits the total plutonium load in mixed oxide (MOX) fuels to <12 w/o. This is a potential restriction with poor fissile quality plutonium. Instead, a Th–Pu fuel could allow significantly higher total plutonium loads (up to ~18 w/o), giving more flexibility for plutonium re-use in LWRs. Therefore, the Th fuel cycle could provide a possible way to manage plutonium stocks with poorer fissile quality and to allow time for thorium–plutonium MOX qualification, supplementing a U/Pu recycle strategy.

The thorium fuel cycle with full recycle will require a long term R&D programme that commercial companies cannot be expected to commit to funding and therefore will require government or supra-national investment. Globally there are thorium R&D programmes in Canada, Europe, India, Norway, China and USA. In Europe, there have been thorium projects under 5th Framework and there were historic R&D projects on thorium, including deployment in HTR and PWR. Within Gen IV, the thorium fuel cycle forms a small part of the MSR programme and also is an option for the Super Critical Water Reactor (SCWR) being led by Canada. India currently is in a leading position, with irradiation test programmes approaching commercial scale. Norway is carrying out experimental scale irradiation testing. Research requirements include:

- Irradiation testing of thorium fuel rodlets
- Thorium fuel properties measurements
- Fuel performance code development for thorium fuels and validation
- Qualification of ThO fuels for deployment in commercial reactors
- Remote fuel fabrication and design of commercial fuel fabrication plants to the point where meaningful construction and operational costs can be estimated
- Development of thorium reprocessing methods, including an understanding of waste form characterisation.

Prospects

Deployment times for utilisation of the thorium fuel cycle at commercial scale are necessarily very long. Licensing of thorium fuels in current reactor types will require fuel qualification, with lead times estimated at 10–15 years, largely determined by the time required for in-core irradiation testing. The development of new reactor designs specifically for thorium fuels will take longer. Initial cores for thorium breeder systems will need to use U-235 or plutonium as the

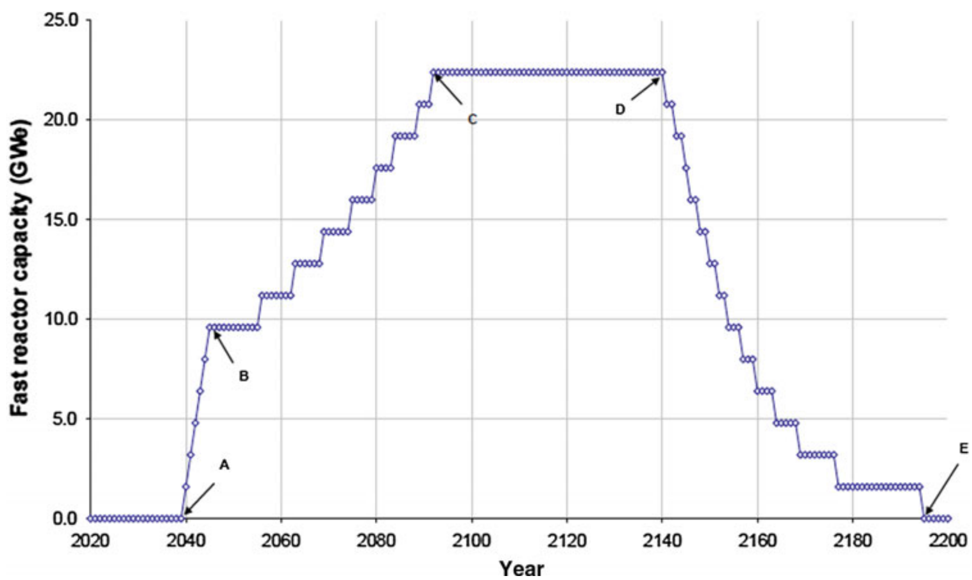


Fig. 2 Hypothetical capacity of a self-sustained breeding system

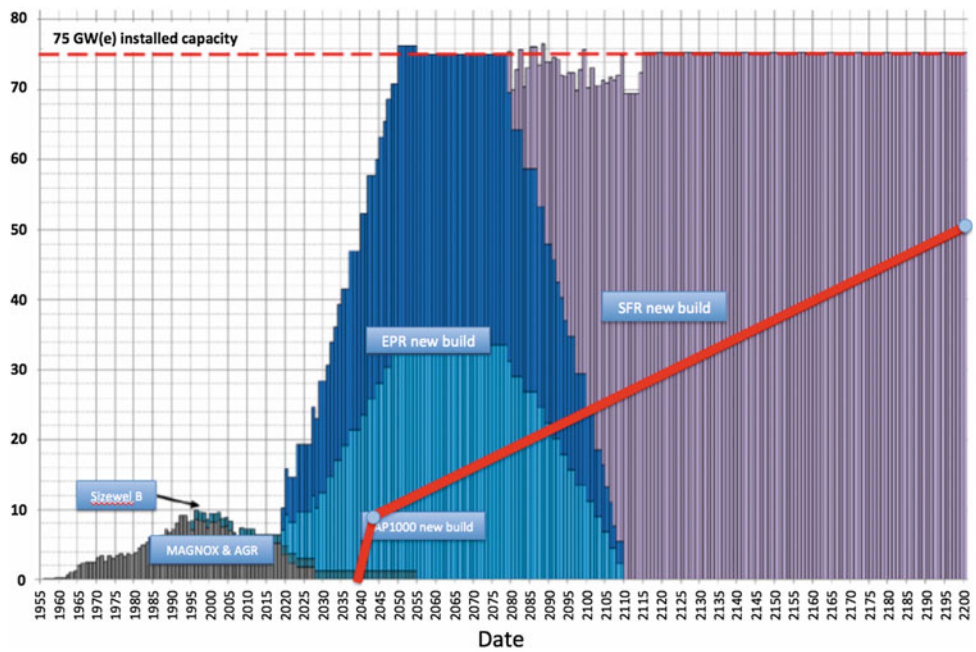


Fig. 3 Illustrative transition to a self-sustaining fast reactor fleet

fissile driver until such time as U-233 breeding reaches equilibrium. Doubling times for practical reactor designs tend to be very long and the prospect of a fully self-sustained thorium cycle is only realistic on a timescale approaching the end of the century (see Fig. 2, which illustrates the typical timescales needed for self-sustained growth in capacity of a realistic breeder reactor system and Fig. 3, which illustrates the timescales for a scenario which transitions to a self-sustained breeder reactor fleet). The full benefits of thorium recycle in terms of reducing uranium demand and lower radiotoxicity will not be achievable until the self-sustained equilibrium is established. A major impediment to the deployment of thorium fuel cycles will be the need to develop an entire new fuel cycle infrastructure to complete against the established uranium-plutonium fuel cycle. However, an even more important factor is that currently utilities do not see any clear economic incentives to develop the thorium fuel cycle. While some utilities may be amenable to hosting small scale irradiation tests of thorium fuels in their plants, there is currently little prospect of any of them investing in new reactor and fuel cycle plant designs. Getting the utilities on side will require clear drivers for them to back the thorium fuel cycle and a priority for R&D should be to identify such drivers and demonstrate that they are feasible.