The Reemergence of the Thorium Fuel Cycle: A Special Issue of *Nuclear Technology*

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Thorium was intensively studied from the 1960s to the 1980s in the United States and internationally as a potential basis for future nuclear fuel cycles. After demonstration of feasible thorium fuel cycle concepts, the United States decided instead to pursue liquid metal, fast breeder reactors using uranium and plutonium. Worldwide interest in thorium fuel cycle development continued at a reduced level, with India having invested the most resources. Recently, the thorium fuel cycle has been the subject of renewed interest, partly due to speculated growth in nuclear energy worldwide (hence putting potential strain on uranium reserves) and partly due to the pursuit of advanced reactor concepts designed to enhance safety and economics—which also have the potential to use thorium to further improve fuel cycle performance. This renewed interest often addresses new possibilities for using thorium in the modern era; however, it can be difficult to discern between actual, unique characteristics of the new thorium concepts and misconceptions disseminated by advocates and detractors. Therefore, right now is a good time to discuss experience with the thorium fuel cycle to date, provide an even-handed description of its inherent attributes, and identify some of the data gaps that have yet to be resolved.

The renewed interest in thorium is supported, in part, by a resurgence of national and industrial programs focused on thorium-based nuclear fuel cycles. India has described plans for a three-stage nuclear energy strategy that integrates thorium-based fuels: Stage 1 involves natural uranium–burning pressurized heavy water reactors, to produce plutonium and stockpile it for future use; Stage 2 uses this stockpiled plutonium in fast breeder reactors with thorium blankets to produce ^{233}U (and additional plutonium) and recycles plutonium back to the fast reactor; finally, Stage 3 uses recovered ^{233}U (from Stage 2) in advanced heavy water–moderated, light water–cooled reactors. Currently, Stage 1 is operational, Stage 2 is in advanced testing, and Stage 3 is in advanced design.[1] China is planning to build two experimental molten salt reactors: The first, which is to commence operation in 2017, will use low-enrichment uranium, spherical pebble fuel, and LiF-BeF$_2$ molten salt as the coolant; this is intended to set the stage for a second molten salt reactor (scheduled to commence operation in 2020), which will use thorium-based fluid fuel and include fuel salt processing.[2] China is also considering the use of Canadian-designed fuels in pressurized heavy water reactors, which have the potential to incorporate thorium.[3] Also, Thor Energy is conducting experiments focused on demonstrating fuel manufacturing, materials, and nuclear performance of PuO$_2$-ThO$_2$ and UO$_2$-ThO$_2$ ceramic fuels. Test pins composed of thorium-uranium and thorium-plutonium oxide mixtures are currently being irradiated in the Halden test reactor, and additional testing of thorium-based oxide fuel pins is planned.[4]

Differences in the major technical features of the thorium-^{233}U fuel cycle and the currently implemented fuel cycle, based on ^{235}U and plutonium, present implications for facility design and operation, along with waste disposal. To set the context for this special issue of *Nuclear Technology*, we will discuss some of the major technical features and characteristics that help to frame the dialogue regarding the use of thorium (a more comprehensive summary is found in Ref. 5). Thorium is fertile but does not contain natural fissile isotopes, so external fissile material is required to produce ^{233}U at the onset of fuel cycle implementation. Thorium-based fuels offer the potential for higher conversion ratios than uranium-based fuels in thermal reactors, since (a) ^{233}U has a relatively low neutron capture (nonfission) cross section compared to ^{235}U or ^{239}Pu, (b) ^{233}U produces ~5% more neutrons per thermal fission, and (c) ^{232}Th has a higher neutron capture cross section than ^{238}U. Differences extend to individual fuel cycle operations as well. Natural thorium recovery is simplified by its isotopic purity (avoiding conversion and enrichment requirements), but it can require significant reagent quantities to chemically purify. Thorium fuel fabrication is complicated by higher shielding requirements, especially for reprocessed thorium–based fuels, due to the energetic gamma emitters of the ^{232}U decay chain. Reprocessing of thorium fuels generally requires higher reagent concentrations than for uranium-plutonium fuels, and process efficiencies can be lower. Comparison of the hazards posed by thorium and uranium spent fuels is dependent on parameters such as time frame, geology, and extent of reprocessing, and this frequent source of erroneous information is addressed in this special issue. Thorium fuel cycles have been described by some as proliferation resistant because of their external gamma radiation field (from the ^{232}U decay chain); however, today it is generally agreed that these advantages can be overstated—the particular technical challenges of safeguards in thorium-based systems are introduced in this special issue.

This special issue of *Nuclear Technology* represents a spectrum of recent thorium-related work, across a number of fuel cycle disciplines, and also provides some perspective on past international thorium fuel cycle operations. This continued conversation builds on a renewed technical dialogue on thorium, beginning with three dedicated sessions on the thorium fuel cycle at the GLOBAL 2013 International Nuclear Fuel Cycle Conference, held September 29–October 3, 2013, in Salt Lake City, Utah (summarized in Ref. 6), and continuing with a special Thorium Fuel Cycle technical track at the 2014 American Nuclear Society (ANS) Winter Meeting, held November 9–13, 2014, in Anaheim, California, during which 44 papers were presented.

The 12 constituent articles of this special issue of *Nuclear Technology* build on the dialogue that occurred at 2014 ANS Winter Meeting. Topics covered include a summary of thorium-related insights from a recent comprehensive assessment of nuclear fuel cycle options, thorium recovery and purification, and strategies for utilization of thorium-^{233}U in current reactor designs, along with evolutionary and more revolutionary concepts. Additional topics include the back end of the fuel cycle (reprocessing and high-level waste hazards) and systemic issues such as safeguards and security and nuclear safety.

Before closing, we wish to recognize a recent report issued by the Nuclear Energy Agency of the Organisation for Economic Co-operation and Development that presents a broad range of current experience and viewpoints on the use of thorium and that provides important perspective.[7] We hope that this special issue of *Nuclear Technology* will facilitate informed discussion of the thorium fuel cycle among researchers, nuclear industries, and power plant operators by providing concise, up-to-date views on the experiences with, and capabilities of, thorium.

References

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