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Thorium: Crustal abundance, joint production, and economic availability

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ABSTRACT

Recently, interest in thorium's potential use in a nuclear fuel cycle has been renewed. Thorium is more abundant, at least on average, than uranium in the earth's crust and, therefore, could theoretically extend the use of nuclear energy technology beyond the economic limits of uranium resources. This paper provides an economic assessment of thorium availability by creating cumulative-availability and potential mining-industry cost curves, based on known thorium resources. These tools provide two perspectives on the economic availability of thorium. In the long term, physical quantities of thorium likely will not be a constraint on the development of a thorium fuel cycle. In the medium term, however, thorium supply may be limited by constraints associated with its production as a by-product of rare earth elements and heavy mineral sands. Environmental concerns, social issues, regulation, and technology also present issues for the medium and long term supply of thorium.

Introduction

There is renewed interest in the commercialization of a thorium fuel cycle for generating nuclear power (International Atomic Energy Association (IAEA) IAEA, 2005, 2012). Growth in electricity demand, particularly in developing countries, combined with the threat of climate change have driven new or renewed interest in a host of power generating alternatives. Such interest includes conventional and advanced nuclear reactors and fuel cycles, of which thorium is a potential option (IAEA, 2005). The benefits and drawbacks of adopting a thorium fuel cycle compared to a uranium fuel cycle continue to be studied, but wide-spread agreement has formed that thorium is, on average, three to four times more abundant than uranium in the earth's crust (Kademani et al., 2006). The implication is that thorium supply has the potential to last longer, or support a larger reactor deployment, than uranium supply. Crustal abundance, however, is an incomplete measure of potential supply. To draw a more complete conclusion about the potential supply of any resource, one must consider resource *availability*. This paper provides an assessment of the availability of thorium in the medium and long term.

Availability of any mineral resource can be defined in four dimensions. The geologic dimension, of which crustal abundance is a component, describes the physical quantity and characteristics of a resource. The technological dimension characterizes the ease or difficulty of recovering and purifying a resource. The social and political dimension of availability measures how resistant social and political institutions are to the recovering of a resource. Social and political resistance tends to increase as the environmental impact of a mine increases. Finally, the economic dimension measures whether or not a resource is profitable to recover. While these dimensions are interdependent, the focus of this paper will be on the economic measure of availability.

This analysis of economic availability uses two related analytical tools. The first is a cumulative availability curve (Yaksic and Tilton, 2009), which provides a perspective on availability over the longer term (decades). It is a plot of total resources grouped by the type of deposit and the associated costs of recovery. Analysis of the cumulative availability curve for thorium suggests that thorium cost could be comparable to historical average uranium prices. Thorium costs around this level should not be prohibitive to the development of a commercial fuel cycle.

The second tool, a potential mining-industry cost curve, illustrates availability over the medium term (some 5–20 years into the future). It is a more conventional, market-assessment tool, which

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plots the potential production rates of individual mines or deposits given capacity constraints and associated costs. In this study, we base the potential cost curve on known resources of thorium, essentially none of which are developed. The potential cost curve represents a medium-term perspective because the resources contained in the curve would take a number of years to be developed once (and only if) a market for thorium emerges. The potential cost curve highlights the role that by-product production plays in thorium availability. Likely sources of thorium are titanium-sand and rare-earth deposits, some of which would be the lowest-cost sources of thorium. However, by-product thorium supply depends on the profitability of the associated main products, titanium sands and rare earths.

The Background section below discusses briefly the potential demand for thorium and outlines issues relevant to its potential supply as a by-product. The Methodology and data section describes the sources of data and the cost estimation method used in constructing the cumulative availability and potential cost curves. The Results section presents the outcomes from the cost estimation model by deposit or deposit type as well as the cumulative availability and potential cost curves. Finally, the Conclusions section places economic availability of thorium in the broader context of social, political and technical availability.

Background

Thorium's potential use as part of a nuclear fuel cycle has been known and studied for more than 50 years. Over this time, there have been experimental-scale applications in nuclear reactors, but thorium has never been utilized on a large, commercial scale.[1] There are several common reasons given for why a thorium fuel cycle has not been commercialized. First, uranium resources, for the most part, have not limited the development of uranium fuel cycles (Ünak, 2000; Van Gosen et al., 2009). Second, technological hurdles exist that thorium must overcome. For example, thorium fuel fabrication and reprocessing technologies are not mature (IAEA, 2012). Third, some have argued that uranium has received more state support than thorium as nations looked to advance military goals alongside civilian goals (Hargraves and Moir, 2010). These three reasons are by no means a comprehensive listing. However, the drawbacks and merits of incorporating thorium into a nuclear fuel cycle are outside the scope of this paper's focus on thorium availability. Readers interested in issues related to the operations or back-end of a thorium based fuel cycle should refer to IAEA (2005) for a more comprehensive discussion.

Total historic thorium demand, and consequently supply, has been relatively small in terms of quantity. Thorium's primary commercial use until recently has been in mantles for gas lanterns. Over the last two decades thorium has been replaced by more inert materials in such non-nuclear applications (Gambogi, 2013). To meet limited thorium demand in the past, by-product supply has been largely adequate.[2]

The role of by-product production of thorium, or joint production more generally, is key to thorium's historic and future supply. Joint production refers to situations in which multiple products are produced from one operation. At a mine, joint production can be characterized by three types of relationships: main product, co-product and by-product. A main product is a material that contributes such a large portion of revenue to a mine that investment and operating decisions are based almost entirely on the market (prices and production costs) for this material. A by-product, by contrast, is a material whose revenue contributes such a small portion to the total revenue of the mine that the mine largely ignores the by-product market when making investment and production decisions. Because by-products are produced as an indirect consequence of producing another resource, the only costs attributable to them are the additional costs incurred to separate and recover them from the main product of the mine. A by-product is recovered only if its price exceeds these additional costs. Finally, a co-product is a material whose own market, and that of one or more other materials, justifies mine decisions. For this study and in the interest of keeping the cost analysis simple, we consider thorium as either a main product or a by-product, although there might be instances of co-product thorium supply in the future.

Thorium's potential future supply could come in the form of main product, by-product or *twice by-product* (by-product of a by-product) production. Main product thorium could be supplied from thorium mines, as depicted on the bottom-most section of Fig. 1. By-product thorium could potentially come from rare earth element mining and processing, as depicted starting in the middle section of Fig. 1 and flowing down. And finally, twice by-product thorium could be derived as a by-product of rare earth elements, which in turn are a by-product of heavy mineral sand mining as shown starting at the top section of Fig. 1 and flowing down.

As shown in the bottom-most section of Fig. 1, thorium could be mined and processed as a main product from high-grade vein deposits of minerals such as thorite (a thorium silicate, $ThSiO_4$). The capital investment and operating decisions to mine these deposits would be determined by the market developments for thorium (with minor consideration given to potential joint products). As thorium has never been recovered on a commercial scale from thorite, many of the high-grade sources of thorium could require further technological developments in order to be recoverable.

The middle section of Fig. 1, depicting rare earth mining and processing, shows that thorium could be produced as a by-product from rare earth processing. Once thorium is concentrated, thorium could be further processed on the mine site, or the concentrate could be sold to a downstream producer. Due to its radioactive nature and lack of a thorium market today, thorium is considered as a deleterious element or nuisance in rare earth deposits and is treated as waste at rare earth mines. The majority of rare earth elements[3] are produced from the mineral bastnäsite (a rare-earth fluorocarbonate, $LaCO_3F$). The most notable bastnäsite mines are the Bayan Obo mine[4] in Inner Mongolia, China, and the Mountain Pass mine in California. The mineral monazite (a rare-earth phosphate, $LaPO_4$) contributes more modest quantities of rare earth supply, but typically has higher thorium concentrations than deposits which are mined for bastnäsite. The Mount Weld mine of Western Australia, which due to a unique weathering process actually has very low thorium content (IAEA, 2011), is the largest single producer of main product REE supplier from monazite. In addition to these three large rare earth deposits and other mines inside of China, many deposits in various stages of exploration could become rare earth mines. The capital investment and operating decisions of both the prospective and current rare earth

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[1] The World Nuclear Association's webpage on thorium includes a summary of past reactors (WNA, 2014).

[2] Main product thorium mines have existed. For example, Steenkampskraal, South Africa.

[3] REEs with lower atomic weights, typically called “light” REEs are produced and consumed in much greater quantities than “heavy” REEs. A major source of heavy REEs are ion-absorbtion clays in southern China. These clays are not a suitable source of thorium.

[4] The Bayan Obo mine is a main product iron ore mine, but is also the largest single producer of rare earth elements in the world (Long et al., 2010). Thorium at Bayan Obo could be considered as a twice by-product of rare earth elements and iron. However, the Bayan Obo case is relatively unique in this respect.