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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.

*This paper has been written alongside the technical report, Jordan and Eggert (2014).

1 Introduction

Recently, interest in the commercialization of a thorium fuel cycle used for generating nuclear power has been renewed IAEA (2012, 2005). 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, 3-4 times more abundant than uranium in the earth's crust (Kademani et al., 2006). The implication of this statement 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 make a more complete conclusion about the potential supply of any resource, one must consider the resource's *availability.* This paper will provide an assessment of the availability of thorium in the medium and long term.

Availability of any mineral resource can be defined as having 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 (or not) social and political institutions are to the recovering of a resource. Social and political resistance tend 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 plots total resources grouped by the type of deposit and the associated costs of recovery. The second tool, the mining-industry cost curve, is a more conventional, market-assessment tool which plots the potential production rates of individual mines or deposits given capacity constraints and their associated costs. From the analysis of the cumulative availability curve, thorium is found to be available in the long term, at low costs.

The mining-industry cost curve highlights that by-product production constraints, technology, and joint production constraints may present challenges to thorium availability in the medium term. We conclude that a thorium fuel cycle will not be constrained by the physical existence of resources, but in the medium term could be subject to supply issues associated with being produced as a by-product. This is because thorium's overall availability is determined more by its association with profitable-to-mine joint products rather than its crustal abundance.

2 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. 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 still not mature (IAEA, 2012). Making these, and other technological developments may involve many years and significant spending on research. Finally, 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.

Thorium's only minor use in nuclear power applications has kept total historic thorium demand, and consequently supply, relatively small in terms of quantity. In fact, thorium's primary commercial use until recently[1] has been in mantles for gas lanterns. To meet limited thorium demand in the past, by-product supply has been largely adequate.[2]

[1] Over the last two decades thorium has been replaced by more inert materials in non-nuclear applications (Gambogi, 2013).

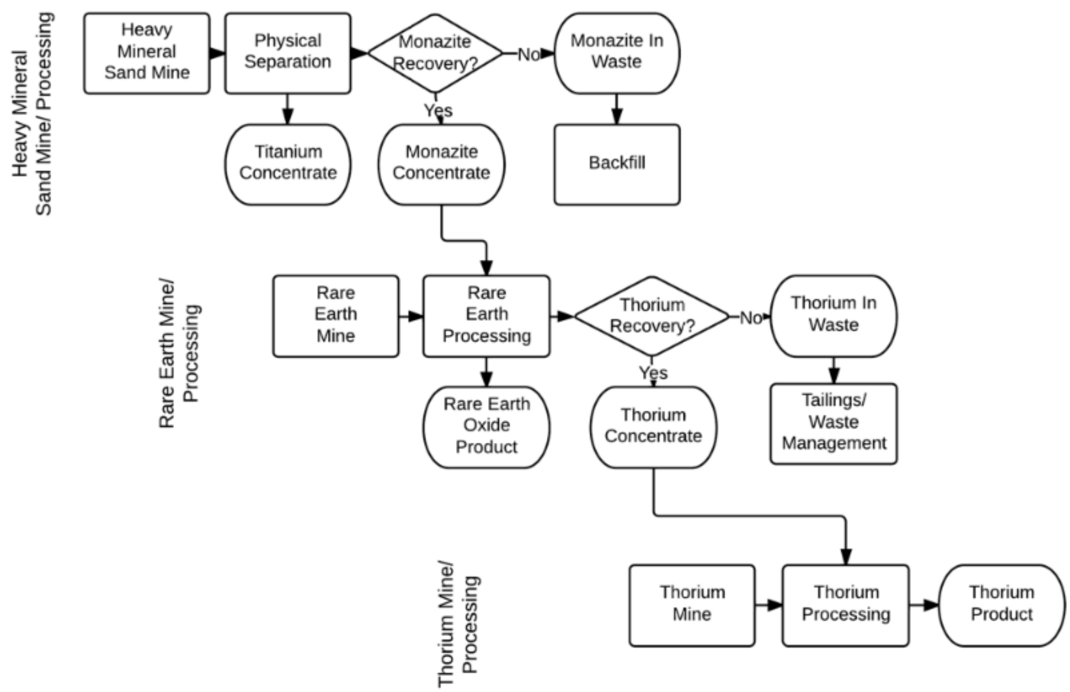
[2] Main product thorium mines have existed. For example, Steenkampskraal, South Africa.

The role of by-product production of thorium, or joint production more generally, is key to thorium's historic and future supply. Joint production can be characterized by three types of relationships at the mine level: main product, co-product and by-product. A main product is a material that contributes such a large portion of revenue to the mine that investment and operating decisions are made based almost entirely on the market (price) 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 investment and production decisions largely ignore its market. Because by-products are produced as an indirect consequence of producing some other resource, the only cost that are attributable to them are the additional costs incurred to separate and recover them from the main product of the mine. By-products will only be recovered if the 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. While co-product relationships are important to historic and potential future thorium supply, we will remove this added complexity simply by referring to main product or by-product supply more generically.

By-product thorium supply is made possible by geologic processes that tend to concentrate thorium with other materials of economic interest (Van Gosen et al., 2009). The most important of these materials, both historically and potentially in the future, have been and are rare earth elements (REEs), titanium, and uranium. Past exploration for uranium and recent exploration for rare earths has led to the discovery of deposits also containing notable grades of thorium. Much lower grades of thorium are found in association with titanium in heavy mineral deposits. If thorium were to be produced from these deposits as a by-product, a high percentage of the mining and milling costs for these ores would be allocated to the main product, rare earth elements or titanium, rather than thorium. If thorium is demanded on a large scale for future nuclear applications, by-product and main product supply may both be utilized in a way similar to that depicted in Figure 1 and explained below.

As shown in the bottom-most section of Figure 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 almost

Figure 1: Thorium Joint Production Relationships



Source: Authors' Representation
This is a generic flowsheet designed to illustrate joint production relationships. It should not be taken to mean that facilities could necessarily process from two distinct types of concentrate feeds.

completely 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 (Young et al., 1980).

The middle section of Figure 1, depicting rare earth mining and processing, shows that thorium could be produced as a by-product from rare earth processing or be combined with other waste to be managed as part of the tailings stream. Today, the majority of rare earth elements[3] are produced from the mineral bastnäsite (a rare-earth fluorocarbonate, $LaCO_3F$). The most notable

[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.

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 operations will be almost completely dependent on the rare earth values recovered. In fact, because it is radioactive, thorium is considered a nuisance element in rare earth deposits, but if the market for thorium justifies, thorium could be processed into a concentrate suitable for further refinement; otherwise it will be treated as waste. The state of technology for thorium recovery from bastnäsite deposits is ambiguous (Jordan and Eggert, 2014), but thorium has been recovered from monazite (principally from heavy mineral deposits) for many decades.

Finally, shown in the uppermost section of Figure 1, thorium could be produced as a twice by-product (a by-product of a by-product) from titanium heavy mineral sand mines. While these mines would primarily be concerned with the recovery of titanium, market developments for rare earth elements (and thorium) may entice such producers to install and operate monazite concentration circuits. Because monazite typically has the highest specific gravity among minerals in these deposits in addition to unique magnetic properties, concentration of monazite requires only physical separation methods (Ito et al., 1991; Ferron et al., 1991), and not more expensive chemical separation. This monazite concentrate could be then further processed to recover rare earth elements as described before. This twice by-product recovery of thorium has been occurring for some time in India (Barthel and Dahlkamp, 1992), which produces and stores thorium for probable future use in the country's nuclear program. Because of the long history of thorium recovery from these heavy mineral deposits and current recovery taking place in India, the technology to recover thorium from monazite (in heavy mineral deposits) is more mature than the technology to recover

[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.(Drew et al., 1990).

thorium contained in bastnäsite or thorite deposits.

3 Methodology and Data

This section describes the sources of data and the cost estimation method used in constructing the cumulative availability and mining-industry cost curves. We first describe the cumulative availability and mining-industry cost curves and their use in assessing the economic availability of thorium produced as a main product, by-product, or twice by-product. We then characterize the data used for the horizontal (quantity) axes of the cumulative availability and of the mining-industry cost curves. Next we overview the method for determining the vertical (cost) axis values, which are the same for both curves, and illustrate this method with an example deposit. Finally, the estimated thorium recovery costs are presented.

3.1 The Cumulative Availability and Mining-industry Cost Curves

The cumulative availability curve is a useful tool for assessing material availability (Tilton, 2003). The curve plots the costs of production of a non-renewable resource over the total (or cumulative) quantity produced. The curve holds technology and exploration (quantity of known and estimated/assumed unknown resources) fixed. It is positively sloped because higher prices justify the recovery of lower grade, and therefore higher cost, resources. Yaksic and Tilton (2009) illustrate the use of the cumulative availability curve for the case of lithium. They note that availability is influenced by three groups of factors. Geologic factors determine the shape of the curve. For instance, a steep curve means that there are only small quantities of high grade/low cost resources. The nature of demand will determine how quickly society moves along the curve (from lower to higher costs sources). Finally, the third group of factors shifts the curve through changes in technology or quantity of resources (due to exploration).

The cumulative availability curve that we construct in this paper will provide an additional extension. Because we are also interested in the nature of joint production of thorium, our cumulative availability curve will plot three cost series, corresponding to main product, by-product and twice by-product thorium recovery cost.

It is important to emphasize that the horizontal axis of the cumulative availability curve, cumulative production, is a stock variable. This is in contrast to flow variables, such as annual or monthly production, which appear on the horizontal axis of a supply curve. Another important feature of the cumulative availability curve is that technology and exploration are held fixed for a given curve, but other variables, such as global refining capacity are not. In this way, the curve presents an analysis of the economic long run, the time frame in which variables under direct control of the mining firm such as labor, capital and land are not constrained, but external variables such as known resources, government policy and the state of technology are fixed. However, at present or at any given point in time in the future, mining firms are faced with a situation where at least one variable under their control is fixed and they are therefore constrained by production capacities.

To provide an alternative perspective on thorium availability, one that utilizes both a flow variable for production and incorporates fixed capacity that mining firms face at any given time, we construct a mining-industry costs curve. This curve uses the same vertical axis as the cumulative availability curve, the average total cost of producing one kilogram of 99.99% thorium oxide. Each mine or deposit is presented on the mining-industry cost curve as a bar, the width of which represents that mine's annual thorium production capacity. In this way, the horizontal axis represents the annual production capacity of the thorium industry as a whole. Using the mining-industry cost curve is particularly relevant in our application, because if thorium is produced as a by-product then the quantities of thorium which can be produced will also be constrained by the quantities of rare earths or heavy mineral sands produced.

Both the cumulative availability and mining-industry cost curves are presented and discussed in Section 4, Results.

3.2 Data on Resources by Deposit Type

The resource data for the horizontal axis of the cumulative availability curve reflects the best estimates to date of known and undiscovered resources. Every two years the NEA/IAEA publishes *Uranium: Resources, Production and Demand* commonly called The Red Book, which includes estimates of thorium resources. The NEA/IAEA categorize these resources into levels of geologic confidence (including undiscovered) for resources deemed to be recoverable at less than \$80/kg (a cutoff also used in their assessment of uranium resources). It should be noted however that because there is little standardization in the classification of thorium resources, these figures are not likely comparable to standardized resource figures for other minerals, such as uranium. Apart from their classification by geologic confidence and recovery cost, the NEA/IAEA also groups thorium resources by five types of deposits: carbonatite, placer (heavy mineral sand), vein, alkaline, and other (NEA and IAEA, 2012). According to the these resource figures shown in Table 3, carbonatite deposits contain the largest quantity of thorium resources, followed by placer, then vein and finally alkaline and other.

3.3 Data on Individual Deposits/Mines

For the horizontal axis of the mining industry cost curve, the data are deposit-specific. Data on thorium grades, quantities and joint products were collected for a selected set of individual thorium deposits and opperating heavy mineral sand and rare earth mines around the world. Included in the selected deposits and mines are: the thorium stockpile accumulated by the United States government, major rare earth mines operating outside of China, a number of the operating heavy mineral sand mines globally ($\approx$24% of world capacity), four rare earth projects that could come into commercial production before 2020, and six thorium deposits in the United States. Appendix B discusses what quantities of thorium might be recoverable if all heavy mineral sand and rare earth capacity were to be included. Deposits and mines were generally selected based on their potential to produce thorium and on information on thorium grades and main product production being generally available. A summary of all deposits included can be found in Table 2

3.4 Recovery Cost Model Overview

For the vertical axis of both the cumulative availability and mining-industry cost curves we develop a recovery cost model that can estimate the costs of thorium recovery as a main product, by-product, or as a twice by-product. To date, the only detailed attempt identified in the public domain to quantify the cost of thorium mining, milling and refining is Young et al. (1980). Young et al. (1980) used engineering process flow and discounted cash flow analysis to assess the costs of extracting thorium as a main product from deposits in the United States. Since the Young et al. (1980) study was conducted, the markets for rare earth elements have developed considerably as new end-uses for very pure rare earth oxides (REO) have developed. Such market developments could make it attractive for deposits to be developed primarily for their rare earth resources with thorium produced as a by-product. Depending on the deposit, considerable cost savings are associated with thorium being produced as a by-product as opposed to a main product.

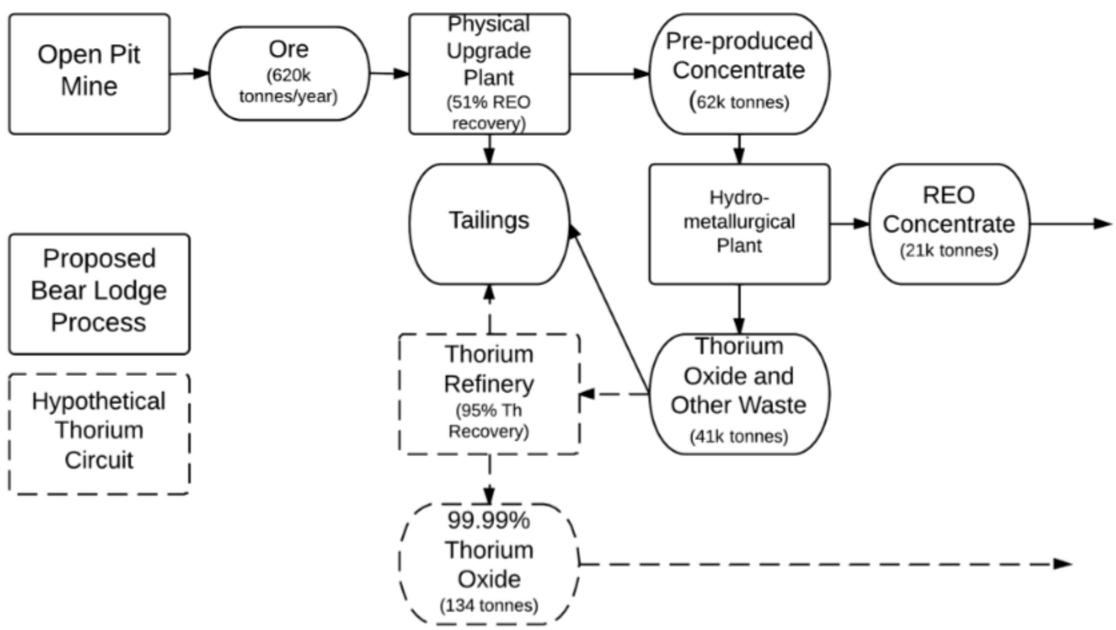
To estimate costs for by-product thorium recovery, we start with the Young et al. (1980) hypothetical monazite refinery flow sheet[5] and associated cost capital and operating cost estimates. Capital costs include buildings and equipment, a feasibility study, environmental impact statement, contingency and tailing management. The capital cost estimates in Young et al. (1980) are depreciated and annualized using a fixed charge rate, which incorporates tax and time value of money effects. The costs incurred jointly for thorium and rare earths are not allocated to thorium if it is produced as a by-product and are therefore removed. This separation of thorium from rare earth elements occurs during the solvent extraction phase and forms a rare earth concentrate and a thorium (waste) stream. A firm wishing to further concentrate thorium after this separation would need to install a by-product circuit which would have a fixed capacity. The input capacity required to handle the daily thorium waste stream from a hypothetical or operating mine is determined based on materials balance and flow, with given or assumed recovery values at each stage. This capacity value is used to scale Young et al. (1980) hypothetical plant operating and capital expenditures to the daily operating capacity of the new plant. Finally, using the tonnes of thorium contained in the waste input, the total plant costs are divided by the tonnes thorium produced to yield a unit cost of production. With this model, only three input variables are necessary to estimate a mine's thorium recovery cost: daily ore input capacity, grade of thorium in ore, and the recovery rate.

[5]The technology underlying the flow sheet in the 1980 study would not be fundamentally different from technology used today.

3.5 By-Product Cost Estimation Example: Bear Lodge, Wyoming

The Bear Lodge deposit in northeastern Wyoming is currently being explored by Rare Element Resources, Ltd. as a potential rare earth mine. This deposit makes an excellent example to use for our by-product cost estimation method for several reasons: (1) the project is an advanced rare earth project in North America, with NI-43-101 compliant resource statements[6]; (2) of prospective rare earth mines, it has a reasonable chance of coming into commercial production; and (3) the deposit was one considered by Young et al. (1980) to be a potential thorium main product mine. These features allow comparison between the Young et al. (1980) study's estimated main product cost and quantity and those estimated by this paper. Figure 2 shows a simplified process flow diagram for the proposed Bear Lodge rare earth mine and associated processing facilities along with a hypothetical thorium recovery circuit.[7]

Figure 2: Proposed Bear Lodge Rare Earth Process with Hypothetical Thorium Circuit



Source: Authors' Representation and Roche Engineering (2012)

[6]A National Instrument (NI)-43-101 statement is one which complies with the Canadian Securities Administrators' set of standardized rules and guidelines for defining mineral resources and reserves for listing on Canadian stock exchanges.

[7]To be clear, this example is hypothetical; Rare Element Resources has no announced plans to handle thorium in any way other than as a waste product to be managed.

Bear Lodge's mine plan[8] calls for 620,000 tonnes of ore per year to enter the physical separation plant. This ore, on average, contains 20,000 tonnes of rare earth oxide, and an unspecified quantity of thorium. The physical separation plant creates 62,000 tonnes of pre-produced concentrate per year. We calculate that this plant is able to recovery 51 percent of the rare earth values. Based on reported grades, this concentrate also contains 142 tonnes of thorium oxide. Next, the pre-produced concentrate is shipped to the hydrometallurgical plant which produces a final product of 21,000 tonnes of rare earth oxide concentrate. During processing at the hydrometallurgical plant, we assume all of the thorium is separated and combined with other material into a single waste stream. This assumption is reasonable because thorium is an impurity and should only be present in minimized quantities in rare earth concentrate product. Therefore, a plant designed to recover all thorium from the waste stream would require a capacity of 41,000 tonnes of material per year. Thorium is assumed to be recovered and purified at a 95 percent rate (the rate used by Young et al. (1980)) from this waste material, yielding 134 tonnes of 99.99 percent purified thorium oxide product.

We use the capacity information from the materials flow to scale the costs for the hypothetical monazite recovery plant described in Young et al. (1980). There are two different factors required for this scaling calculation, one for fixed costs where economies of scale may exist and one for variable costs which change linearly with the quantity of ore processed. We use the following equation, typical in mining engineering cost studies (Darling, 2011) to perform the scaling associated with fixed costs:

$$Cost_{new} = (Capacity_{New}/Capacity_{Old})^{0.7} Cost_{Old} \tag{1}$$

Where $Cost_{new}$ is the cost for the Bear Lodge Th recovery facility, $Capacity_{New}$ is the required capacity of the Bear Lodge facility, and $Capacity_{Old}$ and $Cost_{Old}$ are the capacity and costs, respectively, of the hypothetical Palmer recovery facility estimated by Young et al. (1980). The parameter 0.7 is term related to economies of scale, and is the same one used by Young et al. (1980). The scaled Bear Lodge costs can be found in Table 4 of Appendix A. Next, capital costs are annualized to Bear Lodge's assumed mine life, 19 years, using a fixed charge rate, which

[8] See Roche Engineering (2012) for the Bear Lodge Mine Plan

incorporates tax effects and discounting. This fixed charge rate is the same used by Young et al. (1980), 0.2338. This produces the last necessary information for the availability and cost curves: annual operating costs, annualized capital costs and unit production costs, which are presented in Table 1. Depreciable Assets are calculated by multiplying the fixed charge rate of .2338 by the Total Depreciable Capital Investment of \$8,438,000, found in Table 4 of Appendix A. Working Capital of \$700,000 is the only non-depreciable asset, and is spread out over a 10 year period.

Table 1: Bear Lodge Scaled Production Costs

Depreciable Assets (\$000s)	1,973
Non-Depreciable Assets (\$000s)	70
Annual Operating Costs (\$000s)	10,302
Annual Production Cotsts (\$000s)	12,345
Annual Production ('000 kgs)	134
Levelized Production Cost (\$/kg)	92.13

The final by-product cost of production for Bear Lodge, \$92.13/kg ThO_2 is significantly lower, as expected, than the escalated cost that Young et al. (1980) found for main product recovery from the same deposit, \$345/kg.

3.6 Cost Estimates for Individual Deposits/Mines

A process similar to that described for Bear Lodge was applied to selected deposits globally that would produce thorium as a by-product or a twice by-product. The costs to recover thorium as a main product are escalated without other modification from Young et al. (1980). Table 2 shows a summary of the deposits included in the cost estimation, grouped by joint production relationships and ordered by unit production cost. The cost and capacity figures shown in Table 2 relate directly to those in Figure 4, the mining industry cost curve. Complete sources of data and the assumptions used to calculate cost for each of these deposits can be found in Jordan and Eggert (2014).

Table 2: Potential Sources of Thorium by Joint Product Relationship and Cost (2013 USD)

	Deposit/Mine	Country	Owner	Status	Mine Life	Cost ($/kg)	Capacity (tonnes/y)
Twice By-product	Richards Bay	S. Africa	RBM, Rio Tinto	Operating[1]	30	7.98	1683
	Murry Basin	Australia	Iluka	Operating	6.5	8.01	859
	Jacinth Ambrosia	Australia	Iluka	Operating	14	9.40	509
	Perth Basin	Australia	Iluka	Operating	12	14.04	177
	Concord, Virginia	USA	Iluka	Operating	20	19.06	93
	Orissa	India	Indian Rare Earths	Operating	NA[2]	19.43	240
By-product	Steenkampskraal	S. Africa	Great Western	Pre-Feasability[3]	10	3.56	1176
	Bokan Mountain	USA	Ucore	PEA[3]	11	46.54	29
	Mountain Pass	USA	Molycorp	Operating	30	76.06	67
	Bear Lodge	USA	Rare Element Res.	Pre-Feasability	19	92.13	134
	Mt. Weld	Australia	Lynas	Operating	20	127.96	94
	Arax	Brazil	MBAC	Pre-Feasability	40	196.51	373
Main Product	Stockplies	USA	US Government	"Deposit"[4]	NA[5]	17.84	3168[5]
	Hall Mountain	USA		Deposit	5	40.38	918
	Wet Mountains	USA		Deposit	5	49.04	693
	Lemhi Pass	USA		Deposit	14	85.01	1384
	Palmer	USA		Deposit	20	86.85	2918
	Bald Mountain	USA		Deposit	20	300.44	273
	Conway Granite	USA		Deposit	20	417.20	1289

Sources for costs and capacity: By-product and twice by-product: this study's estimates and various public sources, see Jordan and Eggert (2014). Main product: escalated from Young et al. (1980).

[1] Operating heavy mineral sand or rare earth mine.

[2] The Orrisa facility recovers rare earths and thorium from heavy mineral sands from across India. India's heavy mineral sand resources are extensive.

[3] Three stages of feasibility studies are generally conducted in succession to evaluate the economic acceptability of a mining project. The first stage, the preliminary economic assessment (PEA) has a large degree of associated uncertainty, +/- 40-50%. The next stage, the pre-feasibility study, increases the confidence to around +/-25%. The final stage is the definitive or bankable feasibility which is designed to reduce uncertainty to +/-10%.

[4] The US thorium stockpile was disposed of in Nevada, but could be utilized if unearthed and refined.

[5] The capacity and longevity of stockpiles will depend on demand. The quantity has been modified from Young et al. (1980) to reflect the quantity that is actually contained at the Nevada site.

3.7 Cost Estimates by Deposit Type

In order to construct the cumulative availability curve, costs are assigned to the four deposit types categorized by the NEA/IAEA[9]. Costs are further distinguished as either being main product costs, by-product costs, or twice by-product costs (only in the case of placer/ heavy mineral sands). For example, the Mountain Pass rare earth mine is a carbonatite deposit where thorium could be produced as a by-product. Using the estimation process described earlier, the cost of producing pure thorium oxide as a by-product from Mountain Pass would be approximately \$76.06/kg. These assignments, organized by deposit type, are described in the text below and in Table 3.

By-product recovery costs were estimated for three carbonatite deposits, Mountain Pass, Mt. Weld and Araxá. As shown in Table 2, these by-product recovery costs ranged from \$76-\$197/kg. No main product recovery costs were estimated for this deposit type because such estimation would require "ground-up," mine engineering which is outside the scope of this study.

By-product and twice by-product recovery costs were estimated for six placer deposits. As shown in Table 2, costs for twice by-product recovery in these six placer deposits ranged from \$8 to \$19/kg. If however, thorium justifies recovery as a once by-product, all of the joint rare earth and thorium refining costs should be allocated to thorium. This adjustment raises recovery costs for these same five deposits to the range \$65 to \$156/kg. Finally, if thorium were to be produced as a main product from placer deposits, its recovery cost would jump dramatically. This recovery cost estimate has been escalated from the one conducted by Young et al. (1980), who found main product placer recovery so expensive relative to other sources of main product thorium they give only one lower bound estimate for recovery.

Five vein type deposits have estimates for by-product and/or main product recovery costs. The basis for the by-product recovery cost range presented in Table 3 are the Bokan Mountain and Steenkampskraal deposits, while the basis for the main product recovery cost range are the Hall Mountain, Wet Mountains and Lemhi Pass deposits.

Only two alkaline rock type deposits were assessed, Bear Lodge as a by-product and as a main

[9]There is some deposits which categorization is more ambiguous. When available, we assign deposits based on the deposit type listed on the IAEA ThDepot database.

product (by Young et al. (1980)) and Conway Granite as a main product. These estimates come directly from those presented in Table 2.

Table 3: Potential Thorium Production Costs by Deposit Type (2013 USD)

Deposit Type	World Thorium Resources[1] (1,000 Tonnes)	Main Product Cost[2] ($/kg)	By-product Cost[2] ($/kg)	Twice By-product Cost[2] ($/kg)
Carbonatite	1,900	*Note A*	76-197	*Note B*
Placer deposits	1,500	>760	65-156	8-19
Vein-type deposits	1,300	40-85	3-47	*Note B*
Alkaline rocks	1,120	345-417	92	*Note B*
Other	258	*Note A*	*Note A*	*Note B*

1 Data from (NEA and IAEA 2012)
2 This studys estimates
Note A: No resource in this category had cost estimated in this study.
Note B: Twice by-product production is only applicable in the case of placer deposits.

4 Results

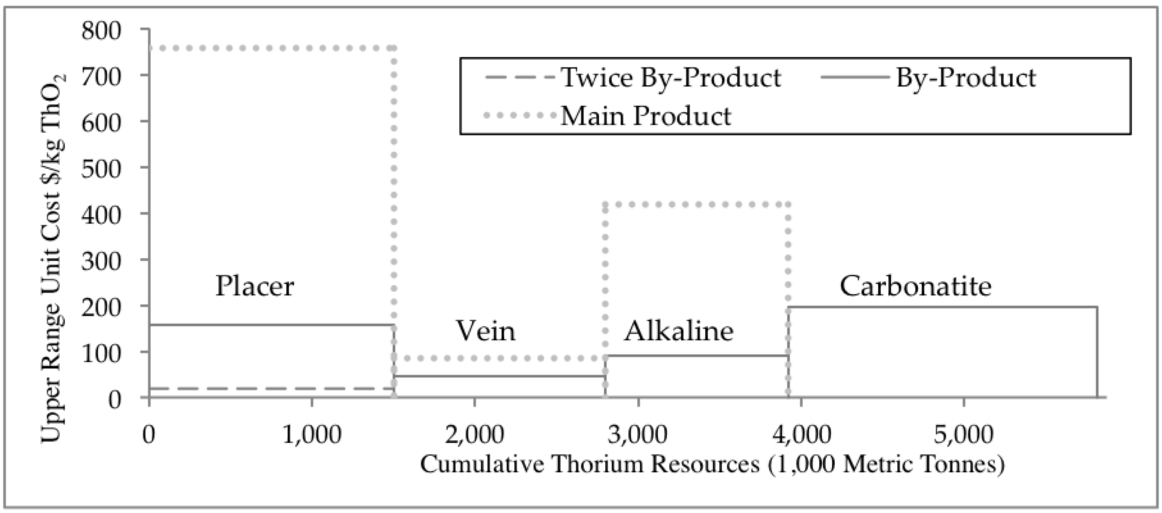
This section presents the cumulative availability and mining-industry cost curves. For both curves, we discuss the implications of the shape of the curves and the associated impact on availability. We then use a constructed demand scenario from Appendix C to illustrate how society might move along the curves. Finally, we discuss how the curves might shift as a result of new exploration or changes in technology.

4.1 Thorium Cumulative Availability Curve

Figure 3 is a graphic representation of the information in Table 3. Deposit types are sorted on the figure by the most likely and least costly means of recovery. Under this organization: twice by-product recovery from placer is the lowest cost, by-product from vein is the second least cost, and so-on. The cost values presented in the figure represent the high-end number from the range in Table 3.

Particularly important in the cumulative availability curve is analyzing the curve's slope, as well as the points in cumulative production where cheaper sources of supply give way to more expensive sources, and how much of a "jump" is associated with these points. As Figure 3 shows, the slope of the curve is relatively benign in terms of cost escalation (given by-product or twice by-product production). Furthermore, the largest "jump" comes if carbonatite resources must be employed to meet demand, but this is only after millions of tonnes of other resources are extracted. Figure 3 also shows the striking benefits of producing thorium as a twice by-product, over single by-product or main product production. In fact, it would be very difficult to imagine thorium being recovered as a main product from placer deposits.

Figure 3: Cumulative Availability Curve: Thorium Resources by Potential Production Costs



Source: Resource quantity data from (NEA and IAEA 2012). Cost data from this study: high value from each range in Table 3. Dollar units are 2013 USD.

To illustrate how society might move along the availability curve, we draw from a global demand scenario constructed in Appendix C. In the scenario, there is a 45 year "ramp up" period where thorium demand grows. After 45 years we assume demand remains constant. Demand is based on a fuel burnup of 10 tonnes/GWe*yr. After the 45 year ramp-up, we assume a total installed capacity of 373 GWe (See Appendix C), a 100% capacity factor, and a steady state, closed fuel cycle. Using these assumptions, cumulative demand is assessed at 100, 250 and 500 years after the beginning of the scenario. The calculated requirement are 0.313, 0.872, and 1.80 million tonnes of 99.99% ThO_2 for 100, 250 and 500 years of reactor operation, respectively. Note that the units of demand are not the same as the units in the cumulative availability curve. The cumulative availability curve uses resources on the horizontal axis, which are an in-situ quantity. Before the two can be directly compared, we must assume some rate at which in-situ resources can be recovered from the ground and purified. Young et al. (1980) estimate thorium mine recovery rates for various deposits between 60% to 100%, and mill recoveries between 40% and 98%. Average refinery recovery rates are higher, 95% in most cases. For simplicity, we will assume the same recovery rate as the hypothetical Palmer mine, 56%, but note the great deal of uncertainty around this rate.

With an assumed recovery rate of 56%, resources from placer deposits are sufficient for the 100 year scenario. In the 250 year scenario, vein and placer deposits are required. Finally, in the 500 year scenario, known resources from placer, vein and alkaline deposits are required. This assumes our constant demand rate and adequate production of main product rare earths and titanium in order to recover thorium as a twice by-product.

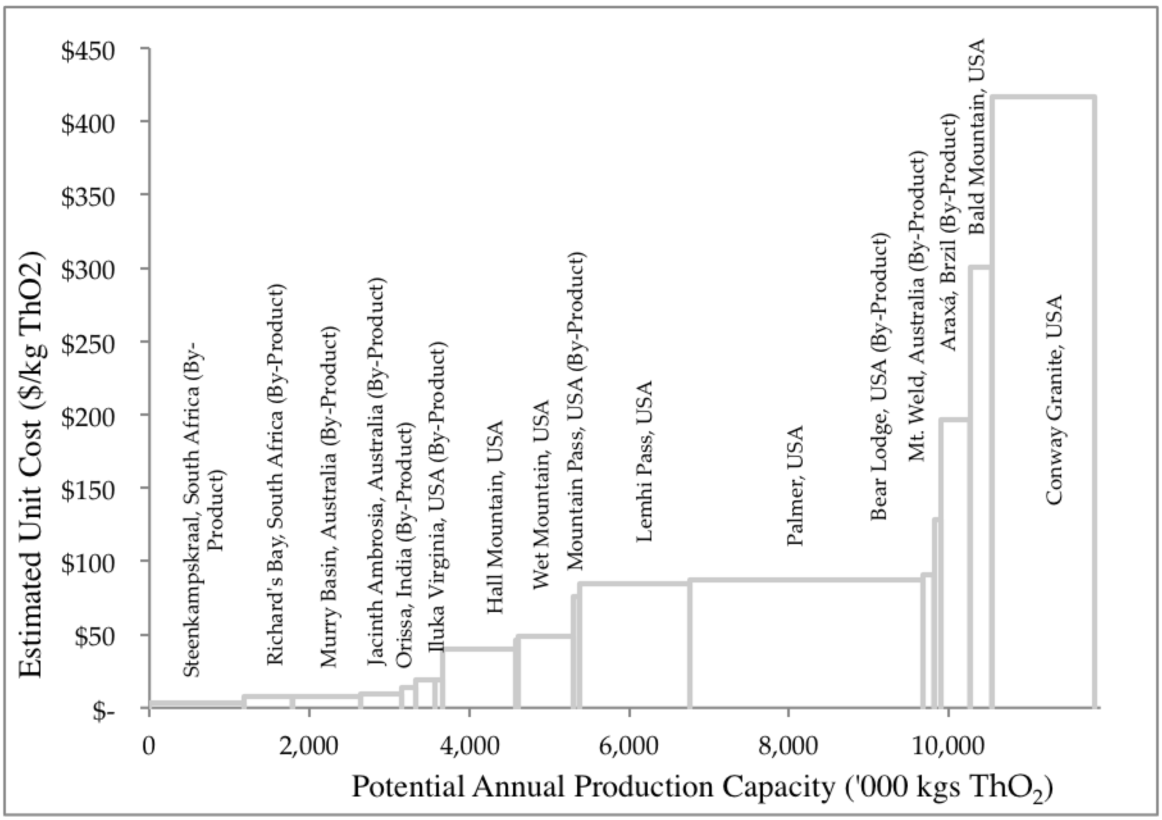
Shifts in the curve will also impact avaialbility. The effects of changing technology over time, which are not accounted for in the discussion above, will have implications for both demand and supply. The importance of these effects to material availability have been demonstrated for other metals such as copper in Tilton and Landsberg (1999). For demand, technological improvement could make reactors more efficient, reducing their consumption. For supply, technology could improve recovery rates or facilitate the discovery of new deposits. The effects of technology over long time periods, such as those calculated above, are especially relevant, but their exact magnitude is unknowable. The limitations of estimating supply longevity in the face of technological uncertainty necessitates the simple conclusion that thorium will be recoverable on the order of centuries at a low cost if by-product and twice by-product sources are available. More importantly, the limitations motivate thinking about thorium supply in the medium term where technology is more predictable and supply constraints are accounted for.

The perspective of availability in Figure 3 is also limited because it presents by-product supply and main product supply on equal terms. For such a presentation to be valid, there would need to be sufficient main product production of rare earths and titanium such that all by-product resources were accessible. The cumulative availability analysis ignores the fixed capacity constraints mines face at any given time. These constraints are particularly important in the mining industry where it takes many years to finance, explore, plan, permit and construct facilities.

4.2 Potential Thorium Mining-Industry Cost Curve

To present a different perspective on thorium availability, incorporating some of the limitations noted about the cumulative availability curve in Figure 3, this section develops a mining-industry cost curve for thorium. Applying the cost estimation methodology developed in this paper, the deposits summarized in Table 2 are plotted on the cost curve presented in Figure 4.

Figure 4: Potential[1] Global Cost Curve for Selected Thorium Resources



Source: This study, see Table 2. Dollar units are 2013 USD.
[1] Includes both currently operating mines and projects in development. Only the Orissa Sands Complex, India has installed capacity for thorium recovery.

More interesting than the physical quantities of recoverable thorium at given costs are the sources of those quantities. Figure 4 shows that annual production from main product rare earth mines such as Mount Weld, Mountain Pass, Bear Lodge and Araxá are expensive relative to twice by-product heavy mineral sources and even some main product thorium mines, such as Hall and Wet Mountains. This can partially be explained by the concentrated state of thorium waste in twice by-product operations, but more importantly illustrates that thorium is an undesirable nuisance element in rare earth mines. It is not uncommon for rare earth projects to advertise their low thorium content as a benefit of their deposit over others. If demand for thorium arises, the desire to seek thorium-poor deposits may change, but absent this demand, deposits with low thorium concentrations may be more likely to be developed.

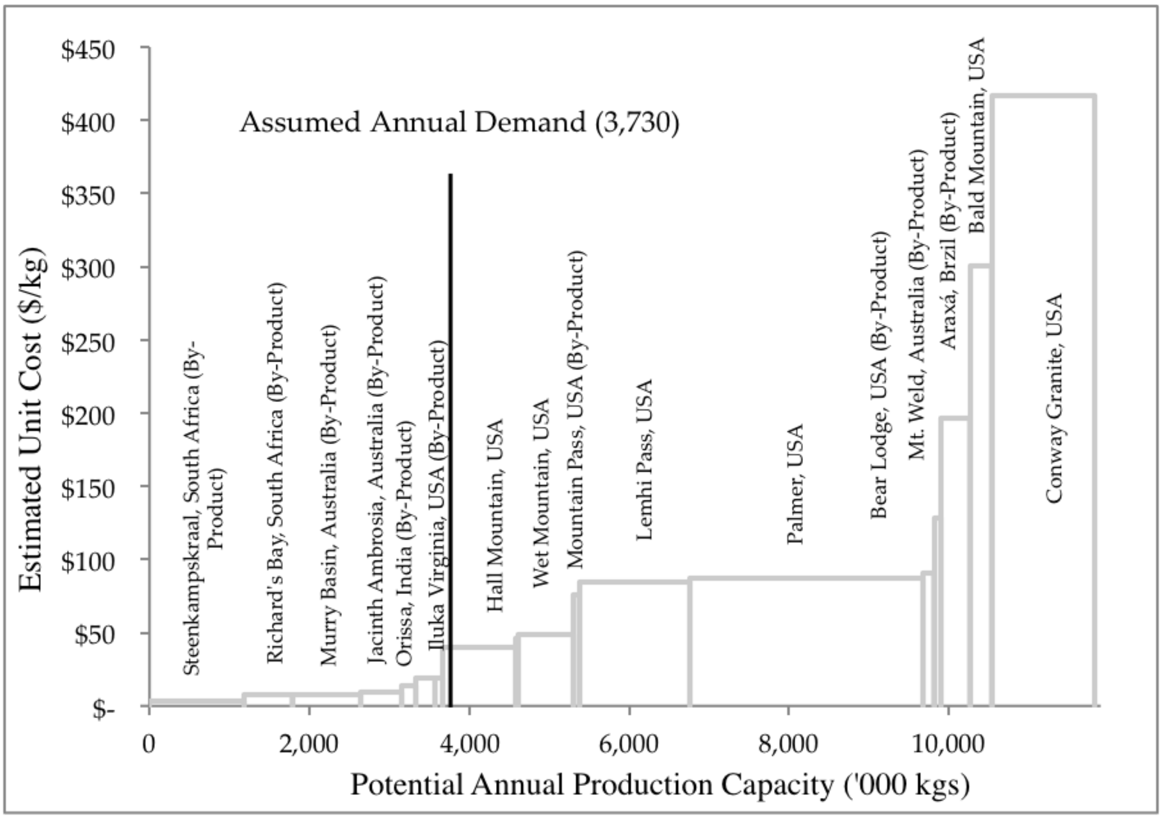
The position of the Steenkampskral mine as the lowest cost source of thorium makes sense, as it historically was one of the only main product thorium mines in the world. The low cost of the Richards Bay is due primarily to its large scale and being able to spread the fixed costs of refining over a larger quantity of production. Richards Bay mine also produced thorium until 1994. The Iluka heavy mineral sand mines of Australia, Murry Bay, Jacinth Ambrosia, and Perth Basin, see relatively low costs because of the assumed concentration of monazite entering the hypothetical rare earth and thorium separation plant. This concentration is assumed to be the same as the Orissa Sands Complex in India.[10] Mt. Weld has a high estimated costs due to the low grade of the rare earth separation plant feed (40% REO, 0.13-0.16% ThO_2). While the Araxá deposit has a 0.10% grade of thorium in-situ, the processing plan for the proposed mine does not include a physical separation plant. This means the run of mine material will enter directly into the chemical separation plant (the plant used as the basis for cost).

In thinking about the shape of the industry cost curve, the cost to produce thorium seems to rise slowly as new deposits are required to meet annual demand and remains below or around $20/kg, until the first main product mine, Hall Mountain, must enter production to meet demand. Hall Mountain has double the production costs of the cheaper, by-product and twice by-product, sources of supply. However, as noted in Appendix B, more potential annual thorium supply from heavy mineral sand mines is likely to be available than is included in the selected deposits for Figure 4.

[10] As the Orissa Sands Complex is currently the only known facility that concentrates monazite from heavy mineral sands before recovering thorium, it could serve as a model for other such plants. These plants could experience similar recovery factors. See Jordan and Eggert (2014) Appendix D and E for discussion of these assumptions.

To place the mining-industry cost curve into context of annual quantities demanded, we again draw from the scenario developed in Appendix C. In this scenario, maximum annual demand for thorium is assumed to be 3,730 tonnes 99.99% ThO_2 per year. This maximum, plotted on the mining-industry cost curve, is presented in Figure 5.

Figure 5: Mining-industry Cost Curve with Assumed Demand Scenario Maximum



Source: This study, see Table 2. Demand is calculated by assuming a 10 tonnes of ThO_2 are required per GWe per year, and a total installed global capacity of 373 GWe. See Appendix C

Figure 5 shows that even the peak level of annual demand (from the assumed scenario) can be met from our selected by-product and twice by-product sources of thorium and only one main product mine, Hall Mountain. However, the curve presented in Figure 5 does not incorporate all potential by-product production from rare earth and heavy mineral sand mines, as noted in Appendix B. The inclusion of omitted by-product production could meet demand without the need for more expensive main product mines, provided that omitted mines are similar to those included. Including additional sources would add additional "bars" to the curve, widening it overall. This does not override the basic point that for these sources to be low cost, thorium must be produced as a by-product or as a by-product of a by-product.

If including omitted sources of thorium production alleviates the need for main product mines in our industry cost curve and demand scenario, in what circumstances would main product thorium mining be required? In other words, what would a world with main-product thorium mining look like? First, it is important to recognize that main product thorium mining has occurred in the past, at the Steenkampskraal mine in South Africa. The unusually high grades of thorium made mining thorium here as a main product economic. It would not be unreasonable to think that this situation could arise again. Main product thorium mining might also be required if the market for rare earth elements does not sufficiently justify recovery from heavy mineral sand deposits or if heavy mineral sand producers are simply not interested in deviating from their core business.

The mining-industry cost curve will also be affected by the same shifting factors as discussed with cumulative availability, namely technology and exploration.

5 Conclusions

Thorium has been identified around the globe in vein, placer and carbonatite deposits and is almost always associated with rare earth elements as well as titanium minerals in the case of heavy mineral deposits. From the cumulative-availability curve estimated in this study, sufficient quantities of thorium should be recoverable in the long term, at a competitive cost, for many centuries. In the medium term, thorium availability may be more limited from by-product production constraints associated with rare earth and heavy mineral sand mining. In both the medium and long term social, political and environmental considerations and technology could present issues for thorium supply.

Though it has been inferred that thorium production from by-product supply will be sufficient to meet most scenarios of demand at an relatively low cost, several nuances are important to note. If rare earth producers continue the recent trend and seek less thorium-enriched sources of rare earth elements, then thorium may need to be produced as a direct by-product of heavy mineral sand operations rather than a by-product of a by-product. Such a development would involve a dramatic increase in recovery costs.

While not the direct focus of this paper, the other constraints to thorium availability, social, political and environmental issues and the state of technology are also important. Thorium is considered a nuisance material for many rare earth operations because its presence raises social, political and environmental concerns. These concerns will likely persist into the future. Potential constraints also exist because of existing technology, which historically there has been little need to develop. Producing thorium at a large, commercial scale will likely require additional work in this area.

Based on the finding of this study, it is unlikely that the potential development of a thorium based fuel cycle will be undermined by physical quantities of thorium resources or by the costs of extracting those resources. Current figures estimate that five to six million tonnes of thorium resources exist globally and these resources are found by this paper, given our demand scenario, to be physically sufficient for centuries. A significant portion of global thorium resources are contained in placer monazite, a supply source with some history of thorium recovery. Finally, thorium oxide costs are unlikely represent a major portion of total costs for plants, provided that thorium can be produced as a twice by-product, by-product or even, in select cases, as a main product.

A tremendous amount of uncertainty surrounds the ultimate development of a thorium fuel cycle. A number of competing proposals for reactor designs, fuel configurations, and reprocessing options exist. On the front-end, it is uncertain how many more thorium-bearing deposits will be discovered, what kind of recovery technology will be developed, how political and social institutions could respond to thorium mining, or how mining firms will be react to a demand for thorium. What does seem to be clear; thoriums availability for use in nuclear power is far more complex than its crustal abundance.

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A Cost Estimation

Table 4 presents each cost item for the estimated Bear Lodge by-product thorium recovery facility and the scale factor used to scale the cost item from the hypothetical plant cost. Interested readers should refer to Jordan and Eggert (2014) for complete documentation on the cost estimation for all deposits.

The scaling factor used in all Table 4 is calculated using:

$$(Capacity_{New}/Capacity_{Old})^{0.7} = 0.53 \tag{2}$$

Where $Capacity_{New}$ is the required capacity of the Bear Lodge facility, and $Capacity_{Old}$ is the capacity of the hypothetical Palmer recovery facility estimated by Young et al. (1980). The parameter 0.7 is term related to economies of scale, and is the same one used by Young et al. (1980). For costs that scale linearly with plant size, the factor .41 was used (the ratio of "new" and "old"" capacity). Finally, some costs are assumed to be fixed regardless of plant size.

Table 4: Scaled Hypothetical Thorium Recovery Plant to Bear Lodge Capacity

	Hypth. Plant $000s	Resize Factor	Bear Lodge $000s
Capital Expenditures			
Refinery Or Mill Capital Cost			
Building and Equipment	10,949	0.53	5,847
Effluent Control Buildings & Equipment	456	0.53	243
Feasibility Study	387	1	387
Environmental Impact	387	1	387
Contingency	1,564	0.53	835
Tailings Pond	1,383	0.53	739
Total Depreciable Capital Investment	15,126		8,438*
Working Capital	1,716	0.41	700*
Total Capital Investment	16,842		9,138
Operating Expenditures			
Operating Labor	2,488	0.53	1,329
Supervision	207	0.53	111
Maintenance and Repairs	1,503	0.53	803
Operating Supplies	507	0.41	207
Laboratory Charges	406	1	406
Total Direct Costs	5,112		2,856
Indirect Costs			
Plant Overhead	2,304	0.53	1,230
Administrative Costs	576	0.53	308
Total Indirect Costs	2,880		1,538
Total Fixed Operating Costs	7,992		4,393
Variable Operating Costs			
Reagents	7,401	0.41	3,021
Utilities	2,858	0.53	1,526
Transportation	2,549	0	
Total Annual Operating Costs	20,800		10,302*

The figures marked with an asterisk (*) in Table 4, Total Depreciable Capital Investment, Working Capital, and Total Annual Operating Costs are used as inputs into Table 5. Total Depreciable Capital Investment is multiplied by the fixed charge rate of .2338 and Working Capital is annualized linearly over 10 years.

Table 5: Bear Lodge Scaled Production Costs

Depreciable Assets ($000s)	1,973
Non-Depreciable Assets ($000s)	70
Annual Operating Costs ($000s)	10,302
Annual Production Cotsts ($000s)	12,345
Annual Production ('000 kgs)	134
Levelized Production Cost ($/kg)	92.13

B Context for Sample Deposits

Because the medium term supply estimates presented in this paper are for a limited number of selected resources, they do not capture the full extent of estimated global resources. Table 6 presents the resources that have been estimated as part of NEA/IAEAs Red Book alongside the life of mine (LOM) production included in this study. The LOM production is calculated by multiplying the assumed annual production of a given resource by its anticipated mine life. The table shows that less than 6% of global thorium resources are included in the cost analysis.

Measuring thorium in terms of known and estimated resources has limitations in putting included resources into context. Demand for titanium and rare earth elements may continue to drive the discovery of thorium bearing deposits. This would imply that 6.0% should be considered an upper bound of included resources. However, it is uncertain how costly and therefore how available these other resources may be.

Another problem with Table 6 is that it does not distinguish potential main product sources of production from potential by-product and twice by-product sources. This distinction is important as by-product thorium recovery would be derived from titanium and rare earth markets and, in the medium term, supply of these products would be limited by installed capacity. On the other hand,

Table 6: Selected and Total Estimated Thorium Resources by Country

	Low-Range Estimate[1] (Tonnes)	LOM Production Included in this Study[2] (Tonnes)	% of Total Estimated Resources
India	846,500	12,632	1.50%
Turkey	744,000		
Brazil	606,000	15,713	2.60%
Australia	521,000	18,622	3.60%
United States	434,000	180,384	41.60%
Egypt	380,000		
Norway	320,000		
Venezuela	300,000		
Canada	172,000		
Russia	155,000		
South Africa	148,000	90,306	61.00%
China	100,000		
Rest of World	581,300		
Total	5,307,800	317,657	<6.0%

[1] Data from (NEA and IAEA, 2012)
[2] This study

by-product supply could likely come online more quickly than main product sources due to smaller capital requirements. Thinking about these medium term implications it may be informative to see what percentage of current titanium and rare earth supply has been included in industry cost curve analysis. Table 7 below shows the quantity of thorium included both in the industry cost curve (Tonnes Thorium/y by the type of main product it would be produced as a by-product from. Ilmenite and rutile are titanium bearing minerals that are frequently recovered together from heavy mineral sand operations and so by-product thorium cannot be attributed to one or the other. Rare earth mines are also broken into two categories, REO Current Production and REO Unutilized Capacity at Operating Mines. This distinction accounts for the fact that the included potential thorium production in the analysis is estimated based on the installed capacity of the Mt. Weld and Mountain Pass mines rather than their actual 2011 production. The percent of main product supply included in the analysis is calculated from USGS estimates, and this number implies a certain amount of potential thorium supply that has been excluded from the analysis, approximately 7,968 tonnes per year or 246,805 tonnes over the life of the excluded mines. These figures rely on the assumption that titanium and rare earth mines that have been excluded from the cost and availability curve analysis are similar in thorium grade, thorium tonnage and mine life to mines that have been included. In reality, mines included in the curves were chosen specifically for their potential to produce thorium and not for their being representative of other main product mines.

Table 7: Thorium Contained in Current REO and Titanium Mine Production

Main Product	Tonnes Thorium/y[1]	Life of Mine (LOM) Thorium Production[1]	Main Product Mine Supply Included in Analysis[2]	Total Main Product Supply in 2011[2,3]	% Main Product Supply Included in Analysis[1]	Implied Thorium Excluded (Tonnes/y)[1]	Implied Thorium Excluded (LOM)[1]
Ilmenite	See Titanium Total	See Titanium Total	674,100	5,870,000	10.50%		
Rutile			468,600	764,000	59.40%		
Titanium Slag	598	50,495	970,000	2,210,000	43.90%		
Titanium Total	2,242	67,265	2,112,700	8,844,000	23.90%	7,143	214,315
REO Current Production	280	13,008	13,800	106,670	12.90%		
REO Unutilized Capacity at Operating Mines	121	2,784	31,599		100.00%		
REE Total	401	15,792	45,399	138,269	32.80%	820	32,305
Grand Total						7,964	246,621

[1] This study
[2] USGS Mineral Commodity Summaries and Mineral Yearbook
[3] Total 2011 Rare Earth Supply (less India, Brazil, Malaysia) + Mt. Weld, Mountain Pass Capacity

Rare earth production from India (2,800 tonnes REO), Brazil (250 tonnes REO), and Malaysia (280 tonnes REO) has been subtracted from total mine production to prevent double counting as all of these countries produce rare earth from heavy mineral sands, but this small correction does not materially affect the results. As shown in Table 7, 4-5 times more thorium (nearly 7,143 tonnes per year) might be producible annually as a twice by-product from heavy mineral sand operations that are mining titanium today. Approximately three times more thorium (820 tonnes per year) might me available from other rare earth operations not included in the cost curves.

Table 7 has not included some of the potential rare earth mines that were included in the cost and availability curves because Table 7 only includes operating mines. To capture the thorium that could be produced from potential rare earth mines, these mines capacity is simply added to the 138,269 tonnes of rare earth production per year from Table 7 . Total REO main product supply has increased over 57% with the inclusion of these mines. When this potential REO mine supply is added, Main Product Supply Included in Analysis increases by approximately 14 percentage points.

Total rare earth supply in this scenario is 173,563 tonnes per year.

C Hypothetical Thorium Demand Scenarios

Not only is there a great deal of uncertainly about how a potential thorium fuel cycle might develop, but it is still very unclear if thorium will be, or even could be, commercialized. Nevertheless, assessing potential demand for thorium provides context to the quantities of thorium potentially available. So while any demand scenario will be highly speculative, such scenarios are important to understanding potential supply. This appendix develops a simple scenario for demand, and outlines the assumptions used.

A convenient way to characterize the potential total global quantity of thorium demanded annually is as follows:

$$Demand_{ThO_2}/year = \frac{TheoreticalMinimumConsumption}{FuelUtilizationRate} * OperationalCapacity \tag{3}$$

Where theoretical minimum consumption is the quantity of thorium (in tonnes of 99.99% ThO_2) required to generate 1 GWe (1,000 MWe) per year if Fuel Utilization Rate was 100%. Operational capacity measures the total operating capacity of "thorium reactors[11]" in GWe per year.

Assuming a thermal efficiency of 40%, theoretical minimum consumption is calculated to be approximately 1 tonne of 99.99% ThO_2 per GWe per year. We further assume, for a closed thorium fuel cycle operating at steady state, a fuel utilization rate of 10%. Fuel utilization may range from 1%, corresponding with the current uranium fuel cycle, to 100% corresponding with a perfectly efficient process. We will assume a value of 10% for the base case, not only because it is an order of magnitude higher than the 1% case and one order of magnitude lower than the 100% case, but also because it is in line with current Th reactor designs being developed. For example, the FUJI-U3 reactor has a fuel utilization of approximately 6%, after accounting for core disposal after 30 years

[11]Most conceptualizations of a thorium fuel cycle propose reactors that convert fertile thorium-232 to fissile uranium-233. U-233 can then be used as a "fuel." The term "thorium reactor" is used here for simplicity to refer to a reactor that could consume thorium.

of operation.

For operational capacity, we assume that the 435 operating reactors around the world are replaced by a thorium-consuming reactor after a 60-year life. For simplicity, we further assume that no other reactor costruction occurs and thorium-consuming reactors remain operating in perpetuity. These 435 reactors represent 373 GWe of installed capacity, which is the second term in Equation 3. For simplicity, we assume a capacity factor[12] of 100%. See Appendix A of Jordan and Eggert (2014) for a more complete detailing of these assumptions. This scenario is depicted in Figure 6.

Figure 6: Assumed Global Thorium Demand Scenario

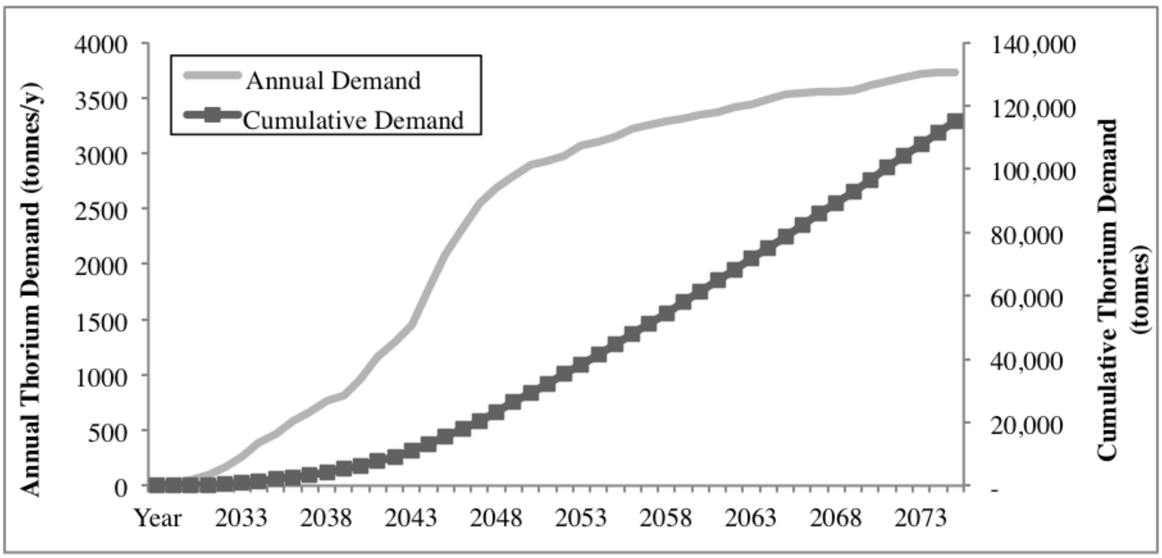

Figure 6 plots annual demand in this scenario on the left axis and cumulative demand on the right axis. In this scenario, the first thorium-consuming reactor comes online in 2029.[13] While specific dates are given for this scenario, one could also think of them generically, with year 2029 being year 0. Demand rises slowly at first before growth accelerates as a number of American reactors retire before finally leveling off. In the year 2074 (or 45 years after the first reactor is converted), the scenario assumes the last reactor converts to thorium and total annual consumption reaches its peak of 3,730 tonnes per year. While one could analyze the thorium requirements at any given level of demand, the peak is particularly relevant in addressing availability because it will

[12]Annual generation divided by capacity

[13]China has recently made commitments to develop thorium reactor technology within a decade, so this a timeline is not unreasonable.

dictate the highest level of production needed and in turn require the highest cost resources to be recovered. It is this peak level of demand that we will use in our assessment of the mining-industry cost curve.

Annual demand is not a relevant measure in the context of the cumulative availability curve. For the cumulative availability curve, cumulative demand is needed. Figure 6 plots cumulative demand through 2074. As with annual demand, there are several ways that one could approach constructing a cumulative demand scenario. We will take a simplified approach and measure cumulative demand at the arbitrary points of 45, 100, 250, 500 years after thorium consumption begins. These later timeframes, 250 and 500 years, are sufficiently far into the future, considering electricity has only in the last century been demand on a large, commercial scale. The first 45 years in this scenario involves the ramp-up in demand shown in Figure6. After 45 years, we will assume annual demand remains constant, as existing thorium-consuming reactors are operated in perpetuity and no addition construction or capacity expansion occurs. Our cumulative demand scenario is shown in Table 8. Our scenario has cumulative demand reaching over 312,960 tonnes by 2129, or 100 years after the first reactor is converted. By 2529, or 500 years after the first "thorium reactor," cumulative demand reaches 1,804,960 by the assumptions used in this study.

Table 8: Cumulative Demand 45, 100, 250, and 500 Years After First "Thorium Reactor"

Scenario Year	Years From First "Thorium Reactor"	Cumulative Demand (tonnes)
2074	45	107,810
2129	100	312,960
2279	250	872,460
2529	500	1,804,960