ASSESSMENT OF THE POTENTIAL OF BY-PRODUCT RECOVERY OF THORIUM TO SATISFY DEMANDS OF A FUTURE THORIUM FUEL CYCLE

FUEL CYCLE AND MANAGEMENT

KEYWORDS: *thorium recovery and mining, thorium fuel cycle, nuclear fuel resources*

TIMOTHY AULT,* STEVEN KRAHN, and ALLEN CROFF

Vanderbilt University, School of Engineering, Department of Civil and Environmental Engineering
2301 Vanderbilt Place PMB 351831 Nashville, Tennessee 37235-1826

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A long-standing concern about the future implementation of thorium fuel cycles has been the availability of a thorium fuel cycle infrastructure, including thorium mineral recovery. Globally, while thorium is known to be a relatively abundant element, there is currently little commercial demand for thorium, leaving many of the world's largest thorium deposits unexploited. However, adoption and subsequent expansion of the thorium fuel cycle may not require "thorium mines" because a number of mining operations (notably titanium and uranium) already extract considerable amounts of thorium, which is presently discarded. Nearly 100 000 tonnes of thorium per year could be recovered from active mine sites, with most of this coming from titanium mining (~80 000 tonnes/yr of thorium) and uranium mining (~9000 tonnes/yr of thorium). This output would be sufficient to satisfy even the most optimistic demand for thorium resources in the near future.

I. INTRODUCTION

Thorium resources are often discussed from the perspective of proven or estimated reserves. Normally, the sizes of thorium reserves are determined by inference, based on estimates for uranium or other mineral resources. As a consequence, thorium reserve estimates have significant variation even among reputable sources, as can be seen in Table I.

The lack of agreement among these sources is not immediately significant, though, since most of these reserves represent deposits that are not presently economically viable for recovery; furthermore, any one of these sources substantially outstrips global demand, which is currently ~100 tonne/yr (Ref. 3). Many of the world's largest thorium deposits are contained in the mineral thorite, which is >50% thorium by mass. Lemhi Pass on the Idaho/Montana border in the United States is one such example of a large thorite deposit, which is thought to contain 56 000 tonnes of thorium oxide.[4] However, there is no current demand for thorium to incentivize the development of even such a rich deposit. In addition to deposits, the United States also has a buried stockpile of >3000 tonnes of thorium nitrate accumulated by the U.S. Department of Energy from 1957 to 1964 (Ref. 5). However, until recently, this material has been viewed primarily from a waste management perspective.

Currently, essentially all of what little thorium that is used (for niche applications such as alloy components, catalysts, and glass) comes from the heavy mineral sands of coastal India. India does not operate any "thorium mines" per se; instead, production is driven by the extensive titanium industry, the bulk of which is used to provide the pigments for white paint. Most of the titanium is produced from the mineral ilmenite (and to a lesser extent, rutile), which is ~30% Ti by mass. India's resources contain ~330 million tonnes of ilmenite, and in 2010 the country produced 767 000 tonnes of ilmenite.[6] The heavy mineral sands that contain ilmenite also contain significant amounts of

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*E-mail: timothy.m.ault@vanderbilt.edu

TABLE I

World Thorium Availability

Country	Reserve Estimate (tonne)[a]	Reserve Estimate (tonne)[b]
India	290 000	846 000
United States	440 000	434 000
Australia	410 000	521 000
Canada	100 000	172 000
South Africa	35 000	148 000
Brazil	16 000	606 000
Turkey	—	744 000
Egypt	—	380 000
Norway	—	320 000
Venezuela	—	300 000
Russia	—	155 000
China	—	100 000
Others		2 004 000
Total	1 400 000	6 730 000

[a] U.S. Geological Survey.[1]
[b] Organisation for Economic Co-operation and Development.[2]

monazite, a rare earth mineral with significant (~5%) thorium content. Monazite is processed for its rare earth content, and it can also be processed to recover thorium. In 2010, India produced ~2700 tonnes of rare earth elements (REEs) and ~100 tonnes of thorium was recovered.[7] Since the thorium-to-REE mass ratio in monazite may, on average, be considerably higher than 1:27, this suggests that not all of the monazite that is processed for REEs has its Th content recovered. A number of titanium mines elsewhere in the world resemble coastal India, in that ilmenite is collocated with monazite. However, there is minimal REE recovery and no thorium recovery reported at any of these sites.

Large tin mines, when the mineral involved is cassiterite, also have a tendency to be collocated with thorium-bearing REE minerals in significant quantities. Another REE mineral, bastnasite, has a thorium concentration about an order of magnitude lower than that of monazite but is surfaced in significant quantities as both a by-product of processing other minerals (such as iron ore) and a primary product for its REE content. Still another REE mineral, loparaite, is recovered in significant quantities from a single Russian mine. While REE minerals represent the most likely (and most quantifiable) sources of thorium, other mineral production activities have the potential to recover by-product thorium as well. In particular, some uranium mines have significant thorium content, which is generally discarded as tailings during ore processing.

The array of thorium-bearing mines with existing large-scale operations raises some interesting questions:

1. Do active mines, with primary products other than thorium, cumulatively constitute a sufficient resource to support a large-scale implementation of the thorium fuel cycle?

2. How many mines would be needed to satisfy potential thorium demand for nuclear energy, and which primary mineral resources appear to make the most sense to serve that purpose?

3. Even if thorium were to be recovered as a by-product of other primary mineral resources, would additional "direct" mining of thorium be required to completely satisfy demand?

Building on previous work,[8] this paper will explore an array of thorium by-product opportunities that exist. The analysis is restricted to large-scale mines (generally with >1000 tonnes/yr of primary product, with exceptions where noted), and only active or nearly active mines (those prepared to open before 2015) are included in the analysis. There are a number of mineral deposits around the world, similar to those included in this study, that are not currently being mined but that might also someday represent significant thorium opportunities. It should be noted that the answers to the aforementioned questions are dependent on what global demand for thorium would actually be. Thus, the topic of potential world thorium demand will be briefly addressed near the end of the paper.

II. THORIUM BY-PRODUCT RECOVERY OPPORTUNITIES

This section describes the opportunities to recover thorium as a by-product from the recovery of minerals produced for nonnuclear applications, as well as from uranium.

II.A. Thorium Recovery from Rare Earth Minerals

The term "rare earth elements" is nearly interchangeable with the elements of the lanthanide series, except that scandium, yttrium, and niobium are often included as REEs. A diverse array of REE-bearing minerals exists, some of considerable abundance, although the majority of these minerals have not generated commercial interest. REE production has increased from ~20 000 tonnes/yr in the 1970s to a recent demand of 130 000 tonnes/yr (Refs. 7 and 9) and a projection of 200 000 tonnes/yr in 2015 (Ref. 7). However, even at recent and projected production rates, total REE production is still less than the markets associated with commodities such as titanium [7 million tonnes/yr (Ref. 10)], tin [230 000 tonnes/yr (Ref. 11)], and iron [1.2 billion tonnes/yr (Ref. 12)]. As such, other primary minerals can drive the justification for mining endeavors even where REEs are present in considerable concentrations.

The following sections describe the primary market contexts in which REEs might viably be recovered, along with the potential for thorium production in these instances.

II.A.1. Titanium Mining

Titanium is a major global commodity that is principally recovered from two minerals: ilmenite and rutile. Both of these are heavy minerals that are found collocated with monazite on a regular basis. Global sources of titanium are widespread, as is shown by Table II.

Of these nations, only two, India and Brazil, presently recover REEs as a by-product of titanium. India's recovery of thorium as another by-product constitutes the only active recovery of thorium worldwide reported.

The availability of information on the thorium content of these titanium deposits is varied. Virtually all of the titanium mining in the United States takes place in one large region, the Piedmont formation, which describes an area between the Appalachian Mountains and the Atlantic Ocean in Virginia, North Carolina, South Carolina, Georgia, and Florida; the only current mines are in Virginia, though Florida and Georgia have operated heavy mineral mines historically.[13] In Australia a number of mined deposits exist. These deposits are highly variable in their composition; however, an average mineral composition of the nation's combined deposits has been estimated: 11.7% rutile, 31.7% ilmenite, 5.9% leucoxene, 21.6% zircon, 2.3% monazite, and 0.4% xenotime.[14] Zircon may also be recovered, as it is the major source of metallic zirconium. Leucoxene is a lower-grade titanium mineral that is not typically recovered in the Piedmont region. This analysis makes the following assumptions: Ilmenite has an average concentration of 31.6% Ti, rutile is 60.0% Ti, and monazite is 5% Th (Ref. 15). It should be noted that both ilmenite and monazite are widely occurring minerals with variable mineral composition; for instance, Indian heavy mineral sand operations have observed Th concentrations in monazite ranging from 5% to 10%, although Indian monazite tends to have slightly higher thorium content than at other locations.[16] Across a string of placer deposits in the coastal eastern United States, monazite was observed to have thorium content ranging from 2.5% to 7.8%, with a mean of 5.7% Th (Ref. 13). In general, while the range of Th contents is variable, most locations' averages seem to hover at ~5% Th, which was deemed to be an acceptable average figure for this study. It is also assumed that the xenotime content is not processed for its Th, although doing so could result in 5% to 10% greater estimates in certain cases. Recovery of thorium during monazite processing is estimated to be 94%, based on experience in India.[16] Thus, potential annual thorium production for each country is computed as

$$[\text{tonne Th}] = 0.94 \times \left([\text{tonne Ti}]_{\text{ilmenite}} \frac{0.05 x_{\text{monazite}}}{0.316 x_{\text{ilmenite}}} + [\text{tonne Ti}]_{\text{rutile}} \frac{0.05 x_{\text{monazite}}}{0.600 x_{\text{rutile}}} \right) ,$$

where x represents the mass fraction of the ore body, which consists of the mineral designated in the subscript; these were obtained from the sources listed in Table III. Mass fraction data were not identified for all nations considered in this analysis. Correspondingly, the mass fractions given by the Australian data are used to extrapolate thorium availability from titanium production for countries other than India, Brazil, and the United

TABLE II

Major World Producers of Titanium in 2012[a]

Country	Annual Ti Production via Ilmenite (tonne/yr)	Annual Ti Production via Rutile (tonne/yr)	Total Annual Ti Production (tonne/yr)
Australia	940 000	480 000	1 420 000
South Africa	1 030 000	131 000	1 161 000
Canada	700 000	—	700 000
China	700 000	—	700 000
India	550 000	25 000	575 000
Vietnam	500 000	—	500 000
Mozambique	380 000	8 000	388 000
Ukraine	300 000	60 000	360 000
Norway	350 000	—	350 000
United States	300 000	—	300 000
Madagascar	280 000	—	280 000
Sierra Leone	—	100 000	100 000
Sri Lanka	60 000	—	60 000
Brazil	45 000	5000	50 000

[a] > 50 000 tonnes/yr (Ref. 10).

TABLE III

Summary of Potential Thorium Recovery from Titanium Mining

Mine Country	Annual Ti Production, All Sources (tonne/yr)	Potential Annual Th Production (tonne/yr)	Source(s)	Mineral Type/Notes
India[a]	575 000 (2700 tonnes/yr REEs)	5900 (230 possible, 100 actual)	Refs. 7, 16, and 17	Mostly ilmenite, some rutile; value in parentheses represents potential based on current REE production rates, not Ti production rates
Brazil[a]	50 000 (550 tonnes/yr REEs)	540 (47)	Refs. 13 and 18	Mostly ilmenite, some rutile; values in parentheses represents potential based on current REE production rates, not Ti production rates
Australia	1 420 000	16 800	Refs. 10 and 14	Mix of ilmenite and rutile; based on average composition of many heavy mineral mines
South Africa	1 161 000	12 600	Refs. 10 and 14	Mostly ilmenite, some rutile; based on Australian mineral ratios
United States	300 000	7600	Refs. 10 and 13	Ilmenite only; based on Piedmont region concentrations
Canada	700 000	7300	Refs. 10 and 14	Ilmenite only; based on Australian mineral ratios
China	700 000	7300	Refs. 10 and 14	Ilmenite only; based on Australian mineral ratios
Vietnam	500 000	5200	Refs. 10 and 14	Ilmenite only; based on Australian mineral ratios
Ukraine	360 000	4000	Refs. 10 and 14	Mostly ilmenite, some rutile; based on Australian mineral ratios
Mozambique	388 000	3900	Refs. 10 and 14	Ilmenite only; based on Australian mineral ratios
Norway	350 000	3600	Refs. 10 and 14	Ilmenite only; based on Australian mineral ratios
Madagascar	280 000	2900	Refs. 10 and 14	Ilmenite only; based on Australian mineral ratios
Sierra Leone	100 000	1500	Refs. 10 and 14	Rutile only; based on Australian mineral ratios
Sri Lanka	60 000	620	Refs. 10 and 14	Ilmenite only; based on Australian mineral ratios
Total	6 944 000	79 800		

[a]Designates country as actively recovering by-product REEs in conjunction with Ti.

States, since these figures represent the averages of many mines located in geographically disparate regions across an entire continent.

As alluded to previously, potential sources of error in these estimates could arise from the application of Australian data to non-Australian sites (which, however, accounts for 61% of the total) and unanticipated deviations in the titanium and thorium content in ilmenite and monazite, respectively. However, even with a particularly wide confidence interval, titanium mining represents, by total potential tonne of thorium recovered, the largest opportunity for recovery of thorium as a by-product. There may be some associated challenges for mines that do not already recover at least some REEs, though (see Sec. III).

II.A.2. Tin Mining

One of the primary ores of tin, cassiterite, is a heavy mineral that is frequently associated with the rare earth mineral xenotime. The worldwide market for tin is considerably less than that for titanium, yet it remains a major global commodity. A few countries dominate global tin production, as can be seen in Table IV.

None of the first five countries, which collectively account for $>85\%$ of global tin production, presently recover any REEs in conjunction with tin mining. However, one minor tin producer, Malaysia, recovers 325 tonnes/yr of REE (from xenotime) in conjunction with mining and processing cassiterite.[13] This is a significant amount when compared to the 3300 tonnes/yr of tin recovered in Malaysia.[11] While xenotime is thought to be a common mineral, its availability is not presently as widely reported as those of monazite and bastnasite. However, xenotime is known to be present in considerable amounts in the tin deposits of China, Indonesia, and Brazil.[19–21] Furthermore, samples of xenotime from Malaysia and China indicate remarkably consistent elemental compositions between locations.[22] Thus, in this paper, xenotime is assumed to have a constant composition of 65% REEs and 3.2% Th (Ref. 15) at all locations.

Few data are available concerning the thorium or rare earth content at most individual mining sites. No records of monazite and xenotime could be identified for Peruvian tin mining, which generally occurs in conjunction with considerably more lucrative copper mining, in deposits that are significantly different from the heavy mineral

TABLE IV

Major World Producers of Tin in 2012[a]

Country	Annual Sn Production (tonne/yr)
China	100 000
Indonesia	41 000
Peru	29 000
Bolivia	20 000
Brazil	11 500
Other countries	26 500
Total	230 000

[a] > 10 000 tonnes/yr (Ref. 11).

deposits observed in China and Malaysia. Bolivia appears to have some monazite and xenotime in its tin deposits, but the monazite tends to be an unusual variety with virtually no thorium.[23] Thus, Peru and Bolivia were not evaluated as potential tin-based thorium sources. China, Indonesia, and Brazil all have clear documentation of high monazite and/or xenotime content with their tin ores.[19–21] The ratio of REE/Sn production is based on what is currently achieved in Malaysia, and the potential production of Th is based on the composition of xenotime (which is similar to that of monazite). Table V highlights summarized potential thorium recovery from tin mining. Since the nature of cassiterite-xenotime collocation is not reported for most minor tin producers, other countries are not included in this analysis. However, it is likely that total thorium availability is slightly higher than the figure given in Table V due to potential contributions from these minor producers.

Uncertainty in these estimates is expected from the application of Malaysian data to non-Malaysian sites, although as mentioned above, China, Indonesia, and Brazil have all been observed to feature significant cassiterite-xenotime collocation.

II.A.3. Iron Mining

This section is restricted to discussing one mine in particular, Bayan Obo in China (see Table VI), because of its unique properties compared to other iron mines. Bayan Obo is a massive mining complex in Baotou, Inner Mongolia, ~600 km northwest of Beijing. The mine principally recovers iron from the minerals magnetite and hematite. In 2006, Bayan Obo produced ~9 million tonnes of iron and steel products.[24] Bayan Obo also contains what is sometimes referred to as the world's largest REE deposit in the form of both bastnasite and monazite.[13] While the size and location of the largest REE reserves can be debated,[13,25] Bayan Obo *is* undeniably the single mine with the greatest current REE production, at 47 000 tonnes/yr (Ref. 13).

A Chinese study reports that the REE-producing portion of Bayan Obo contains 34% iron, 5% rare earth oxides (REOs), and 0.032% Th oxide.[24] Renormalizing to ignore the oxygen content, this equates to ~4.3% REEs and 0.028% Th. An International Atomic Energy Agency (IAEA) report contains similar values: 5% to 6% REOs and 0.04% Th oxide (or 4.7% REEs and 0.035% Th) (Ref. 26). Taking the average of these two sources, the ore is estimated to be 4.5% REEs and 0.032% Th. Thus, on average for the production of 1 tonne of REEs, 7.1 kg of Th is contained in the ore. There may be additional REE content in other portions of the Bayan Obo complex, but data could not be located.

There are other iron deposits of the world where monazite, xenotime, or bastnasite may be present in small amounts. At Sweden's Kiruna iron mine, monazite appears irregularly at various areas of the ore body, although never in particularly high concentrations.[27] Small amounts of monazite have also been observed in

TABLE V

Summary of Potential Thorium Recovery from Tin Mines

Mine Country	Annual Sn Production (tonne/yr)	Potential Annual Th Production (tonne/yr)	Source(s)	Mineral Type/Notes
Malaysia[a]	3300	16	Refs. 11 and 13	
China	100 000	480	Refs. 11 and 13	Derived from REE/Sn ratio observed in Malaysia
Indonesia	41 000	200	Refs. 11 and 13	Derived from REE/Sn ratio observed in Malaysia
Brazil	11 500	60	Refs. 11 and 13	Derived from REE/Sn ratio observed in Malaysia
Total	156 000	760		

[a]Designates country as actively recovering by-product REEs in conjunction with Sn.

TABLE VI

Summary of Potential Thorium Recovery from REE Operations at Bayan Obo Iron Mine

Mine Name	Mine Country	Annual REE Production (tonne/yr)	Potential Annual Th Production (tonne/yr)	Source(s)	Mineral Type/Notes
Bayan Obo	China	47 000	330	Refs. 13, 24, and 26	Carbonatite with mostly bastnasite, some monazite

the regions near the large iron mines of Western Australia.[28] Even at the largest iron mines (other than Bayan Obo), thorium recovery does not appear to be a significant option and thus is not included in this paper. However, future surveys could indicate more encouraging prospects for thorium recovery from iron mining in addition to Bayan Obo.

II.A.4. "Direct" Rare Earth Mining

In addition to the many mines that surface REE minerals in the pursuit of other commodities, some mines in Australia, China, Russia, and the United States have been established specifically for REE recovery. With the exception of Russia, these countries recover bastnasite to obtain REEs. The ore from Australia's Mount Weld mine contains 9.8% REOs and 626 parts per million Th (Ref. 14). Calculations for the Chinese mines is based on Bayan Obo's bastnasite, which has ore containing 5% REO and 0.032% thorium oxide. At Mountain Pass in the United States, the bastnasite contains 2% to 12% REOs and ~0.02% thorium.[26] Russia's Lovozero mine surfaces a unique local ore known as loparite. Loparite is of the perovskite family of minerals, meaning that it contains considerable amounts of titanium and calcium, but its lanthanum, cerium, and niobium content are what drive production.[29] The thorium content of loparite from Lovozero is ~1.3% (Ref. 15).

Production potential of thorium from "direct" REE mining is summarized in Table VII. Most of the entries in Table VII are individual mines; however, certain regions of China are a summation of multiple individual mining sites.

The most significant sources of uncertainty from these estimates are expected to originate from the application of Bayan Obo data to the other Chinese mining regions, although Th content seems to be more widely reported for REE mines than for other types of mines examined in this study.

II.B. Uranium Mining

Rare earth mining, and mining operations that surface coincidental REE minerals, are probably the most well-understood pathways to thorium recovery. However, a number of other abundant minerals with thorium, such as thorite, exist that are not necessarily associated with REEs. Without the potential for products that are presently commercially viable to drive production, these minerals are frequently disregarded. The Lemhi Pass deposit, an extensive thorite vein on the border between the states of Idaho and Montana in the United States, is an example; the ore contains a remarkably high thorium concentration of 0.4% and is located relatively close to the surface.[4] In the U.S. thorium fuel cycle analyses conducted in the United States in the 1970s, Lemhi Pass was often considered the most likely thorium resource (should a demand emerge).[30] However, this demand never materialized.

It seems logical to evaluate the potential for coproducing Th with U, as practices for handling radioactive materials are already in place at these sites. At some locations, thorite and other thorium-bearing minerals can be found in conjunction with uranium minerals. In fact, as in the case of uranothorite, some minerals contain *both* uranium and thorium. The thorium content of the world's major uranium mines varies due to the array of geologies that are currently exploited. However, mines that currently employ the in situ leaching (ISL) technique to recover uranium will likely not be able to recover significant thorium content—even where present. ISL works by using a mildly basic or acidic solution to oxidize uranium to the hexavalent state, where it is relatively soluble and becomes part of the solution "liquor." However, thorium cannot oxidize to the hexavalent state and will remain insoluble and, thus, locked up in the geological formation.[2] This insolubility also means that thorium's abundance in seawater is much lower than that of uranium [0.4 parts per trillion for Th versus 3300 parts per trillion for U (Ref. 31)], and any future deployment of uranium seawater extraction would not be expected to recover thorium.[32]

Table VIII summarizes the world's largest uranium mines that do *not* use the ISL method and their thorium-producing potential. Data for the two Nigerien mines are taken from the ratio of activity from ^{220}Rn (for Th) and ^{222}Rn (for U). Assuming secular equilibrium, it can be inferred that the Th/U ratio at Arlit is 1.21, and Akouta is assumed to be similar to Arlit.[33] The Canadian mines of northern Saskatchewan are promising options for large-scale thorium

TABLE VII

Summary of Potential Thorium Recovery at "Direct" REE Mines

Mine Name	Mine Country	Annual REE Production (tonne/yr)	Potential Annual Th Production (tonne/yr)	Source(s)	Mineral Type/Notes
South China	China	38 400	260	Refs. 13, 24, and 26	Bastnasite; includes multiple mines
Mountain Pass	United States	34 100	230	Refs. 13, 24, and 26	Bastnasite
Mount Weld	Australia	18 800	130	Refs. 13 and 14	Bastnasite; represents high-grade portion of site
Lovozero	Russia	2130	100	Refs. 13 and 15	Loparite
Sichuan	China	8500	57	Refs. 13, 24, and 26	Bastnasite; includes multiple mines
Total		101 930	780		

TABLE VIII

Summary of Potential Thorium Recovery at Largest Non-ISL Uranium Mines[a]

Mine Name	Mine Country	Annual U Production (tonnes/yr)	Potential Annual Th Production (tonnes/yr)	Source(s)	Mineral Type/Notes
Arlit	Niger	3065	3700	Refs. 35 and 39	Sandstone
Akouta	Niger	1506	1800	Refs. 35 and 39	Sandstone
McArthur River	Canada	7520	940	Refs. 34 and 39	Marine sedimentary
Krasnokamensk	Russia	2011	850	Refs. 36 and 39	Mixed granite-volcanic
Kayelekera	Malawi	1268	550	Refs. 37 and 39	Sandstone (Tabular)
Rossing	Namibia	2289	400	Refs. 38 and 39	Magmatic-Hydrothermal
Langer Heinrich	Namibia	1955	340	Refs. 38 and 39	Magmatic-Hydrothermal
McClean Lake	Canada	2100	260	Refs. 34 and 39	Marine sedimentary
Rabbit Lake	Canada	1479	180	Refs. 34 and 39	Marine sedimentary
Olympic Dam	Australia	3390	<1	Refs. 39 and 40	Mixed granite-volcanic
Ranger	Australia	3146	<1	Refs. 39 and 40	Sandstone
Total			9000		

[a] >1000 tonnes/yr.

recovery due to the presence of considerable monazite concentrations in conjunction with the primary uranium mineral, uraninite.[34] A survey of the uraninite in the vicinity of these mines indicated a UO_2 content of 56.29% to 64.29% and a ThO_2 content of 6.46% to 8.65%, yielding an average Th/U ratio of 0.125 (Ref. 35). This is likely an underestimate of the total Th content of the Canadian ores, since this area is known to contain small amounts of monazite amidst the uraninite. However, reliable quantitative data for the amount of monazite in the ores were unavailable, so the thorium contribution from monazite in the northern Saskatchewan area is not included in this study. The Th/U ratio at Russia's Krasnokamensk mine is taken to be 0.42 based on a combination of mineral samples at the site.[36] At Kayelekera in Malawi, a Th/U ratio (0.43) can be inferred from soil and mineral samples from around the mine site.[37] In Namibia, a number of uranium deposits exist in both the central and southern parts of the country, and the Th/U ratio is variable. In the highest-grade regions, though, the ratio is more consistent, ranging from ~ 0.05 to 0.3 (Ref. 38). The median of this range (0.175) is used for both Namibian mines in this analysis.

Given the scale of uranium mining in northwestern Canada, a change to the assumed Th/U ratio in this area could have a dramatic effect on the cumulative estimated Th available from U mining. However, at 9000 tonnes/yr, uranium is still a significant contributor to total Th availability—even with conservative estimates.

II.C. Summary of Potential Thorium By-Product Recovery

Table IX summarizes the potential yield of thorium by-product recovery from commodities described in preceding sections.

It should be emphasized that these estimates entail potentially significant uncertainty; this uncertainty was discussed in each section (above). Only the estimates for titanium account for anticipated material losses during processing, due to a lack of thorium recovery experience from other sources.

III. ANTICIPATED ENVIRONMENTAL IMPACTS OF BY-PRODUCT THORIUM RECOVERY

The presence of thorium often presents challenges due to its radiological hazard. The gaseous radon species that results from ^{232}Th's decay chain, ^{220}Rn (often-called "thoron"), is considerably shorter lived than the equivalent of the ^{238}U decay chain, ^{222}Rn, with half-lives of 55.6 s and 3.82 days, respectively. As a consequence, ^{232}Th generally poses less of a long-distance radiological hazard to the public than ^{238}U, but it can still be a significant on-site inhalation hazard during mining and processing. In the past, thorium-based hazards have impacted cassiterite operations in Malaysia[41] and ilmenite operations in India,[42] among others. The Malaysian facility, in particular, garnered international attention when it became the subject of an IAEA review of its radiological hazards to the Malaysian public.[43]

It should be noted that most of these hazards are already present—whether or not by-product thorium is recovered. During monazite processing in India, individual workers typically receive doses of 3.0 to 7.8 mSv/yr. Normalized to thorium oxide content and accounting for the number of workers, the routine processing of REEs results in an occupational dose of 6.2 person-mSv/tonne of ThO_2 or 8.0 person-mSv/tonne Th (Ref. 43). These processes result in the formation of a Th-bearing hydroxide slurry that is frequently discarded. The slurry is sometimes processed to create a nuclear-grade thorium oxalate product. This incremental processing leads to an additional occupational dose of 1.6 person-mSv/tonne of Th (Ref. 44). In other words, when processing for REEs, most of the radiological dose is associated with processing of the primary product, and refining of Th contributes ~20% to the overall process dose. In the case of uranium mining and processing, radiological safeguards are already in place, and additional impacts from thorium processing would not be expected to significantly impact overall process management.

TABLE IX

Summary of Cumulative By-Product Thorium Availability from Multiple Sources

Primary Commodity	Potential Associated Thorium Yield (tonnes/yr Th)
Titanium	79 800
Uranium	9000
REEs ("Direct")	780
Tin	760
Iron	330
Total	90 700

In addition to the occupational radiological impacts, there is sometimes concern with the return of Th-bearing overburden to the ground. For example, for the Green Cove Springs heavy mineral mine in Florida, the Florida Bureau of Radiation Control required the mine to obtain a license for processing and disposal of technically enhanced naturally occurring radioactive material (TENORM), because the milling process concentrated the radiological material above regulatory thresholds and made it more accessible.[45] At Mountain Pass, prior operations were challenged by the management of radiological content, which led to public opposition following a large release of wastewater over a dry lake.[46] This event was part of the reason for Mountain Pass's initial closure. As these examples indicate, management of TENORM can be a deterrent to heavy mineral mining. However, recovery of by-product Th would remove much of this radiological hazard from the mill tailings sent to disposal. This is arguably a waste management benefit.

IV. ASSESSMENT OF HYPOTHETICAL WORLD THORIUM DEMAND

The foregoing analysis begs the question "how many reactors could be supported if all of the potential by-product thorium (90 700 tonnes/yr of thorium) were to be recovered?" As of 2011, 434 nuclear reactors generate 370.4 GW(electric) of electricity worldwide.[47] Determining the annual thorium requirement for these reactors is complicated by the fact that there are multiple types of reactors using multiple types of fuel. For the purposes of this analysis, to gain an order-of-magnitude estimate of potential thorium requirements, we assume that the entire nuclear fleet is composed of pressurized water reactors capable of generating 1 GW(electric) of power. Assuming a typical specific power for the fuel in the reactor [37.5 MW(thermal)/tonne HM] and thermal efficiency (33%) means that each reactor core contains 80 tonnes HM of uranium dioxide fuel. The fraction of the fuel required each year depends on the fuel management approach being used and typically ranges from 33% for older, lower-burnup fuels to 25% (and perhaps less) for newer, higher-burnup fuels.[48] Here, we adopt the value for newer fuels, which means that each 1-GW(electric) reactor will need 20 tonnes HM of fuel each year.

Using these assumptions, we consider two scenarios. In scenario 1 the reactors are operating on a once-through fuel cycle. For a uranium fuel cycle each reactor would require 20 tonnes HM/yr of low-enriched-uranium fuel. The amount of heat that a nuclear fuel can be allowed to produce and still meet safety requirements depends on how hot it can get at the fuel rod centerline. This, in turn, depends on the thermal conductivity of the fuel and its melting point. The thermal conductivity of pure thorium dioxide is greater than that of pure uranium dioxide, and its melting point is higher than that of uranium dioxide. However, solid solutions of thoria/urania result in conductivities that quickly approach the thermal conductivity of pure urania even at low urania concentrations.[49] Thus, it is assumed that each tonne of thorium dioxide fuel would produce the same amount of heat as a tonne of uranium dioxide fuel, which means that the thorium demand would be 20 tonnes HM/yr per reactor, or ~7400 tonnes HM/yr for the entire nuclear reactor fleet. This thorium consumption rate is ~8% of the annual potential by-product thorium production. While thorium fuel cycle technology has likely advanced to the point where resource utilization could be more efficient than suggested in the estimates here, even for a once-through cycle without reprocessing, scenario 1 is intended to represent an upper bound of potential global thorium consumption. Thus, the low-efficiency assumptions are incorporated.

In scenario 2, the spent fuel from the reactors is reprocessed to recover and recycle the thorium. Assuming that ~3% of the thorium is transmuted or fissioned, and that 2% of the thorium is lost to various waste streams during reprocessing and fuel fabrication, the annual amount of thorium consumed would be 5% of 20 tonnes HM/yr, or 1 tonne HM/yr for each reactor and ~370 tonnes HM/yr for the entire reactor fleet, which is just 0.4% of the potential annual by-product production.

One caveat is that on a system-wide basis, once-through or nonbreeding thorium fuel cycles would require fissile material from an exogenous source to operate, since ^{232}Th is not fissile. A second caveat is that ~10% of the potential by-product thorium comes from uranium mining, which would be reduced to the extent that thorium-based fuels replace uranium-based fuels.

V. CONCLUSIONS

Without opening any new mines, there is the theoretical potential for nearly 100 000 tonnes/yr of thorium to be recovered from active mines being currently operated to recovery materials other than thorium. The most important routes for recovery appear to be from the titanium and uranium mining industries (though demanding additional development to perform such recovery, including the assessment of technical-economic relevance and interest). Of course, sufficient demand will still be required to incentivize the establishment of incremental processing required to obtain nuclear-grade thorium from monazite or other minerals. Even if the entirety of current global nuclear energy production replaces uranium-based fuels with thorium-based fuels, and no reprocessing were implemented, the potential by-product recovery of thorium exceeds the demand by a factor of ~12. In a reprocessing fuel cycle, the required amount of by-product thorium exceeds potential production by a factor of ~250. Of course, total replacement of uranium with thorium would mean that uranium demand would drop considerably, but titanium mining alone is sufficient to meet thorium requirements. A once-through thorium fuel cycle would still require uranium mining and processing to provide enriched uranium or plutonium, but a closed, breeding thorium fuel cycle could eventually be able to rely on natural thorium resources alone.

There are several sources of uncertainty in the estimates presented in this paper. Some of the world's major titanium sources may have significantly less collocated monazite than is observed in Australia, India, Brazil, and the United States. Nonetheless, the consistent simultaneous occurrence of ilmenite and monazite at many sites, in each of these four countries, suggests that titanium is more often collocated with thorium than not. Similarly, a lack of interest in thorium at uranium mining sites has required extrapolation from less desirable information sources, such as the ratio of Th/U in crustal abundance across regions surrounding the specific mine sites. However, studies indicate that while Th and U concentrations tend to vary significantly as a function of position, the ratio of Th/U is a much weaker function of position.[50] Thus, while uranium concentrations are expected to be much higher than average at uranium mine deposits, thorium concentrations are expected to be high at the mine deposits as well.

Therefore, while the specific amount of by-product thorium available has a degree of uncertainty, it has been demonstrated herein that by-product thorium recovery should be able to satisfy foreseeable deployment of thorium fuel cycles by a wide margin. Barriers to implementation of thorium fuel cycles still exist, but resource recovery infrastructure should not be counted among them.

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