Advanced Fuel Cycle Cost Basis Report: Module A2 Thorium Mining and Milling

Nuclear Fuel Cycle and Supply Chain

Prepared for

U.S. Department of Energy

Systems Analysis and Integration

January 2021

INL/EXT-21-61493

Revision 1

REVISION LOG

Rev.	Date	Affected Pages	Revision Description
	2009	All	**Version of AFC-CBR in which Module first appeared**: In 2009 AFC-CBR Module A was separated into Module A1 for Uranium Mining and Milling and Module A2 for Thorium Mining and Milling. Thorium had not been considered in earlier AFC-CBR versions.
	2012	All	**Latest version of module in which new technical data was used to establish unit cost ranges:** 2012 (This new data supported the 2009 ranges, which were used as the basis to escalate to 2017$)
		All	**New technical/cost data which has recently become available and will benefit next revision:** No particular new reports were identified. A search of new reports from MSR proponents who have interest in this issue might be warranted. The original author of Module A2 also suggested that costs associated with byproduct recovery of thorium salts from rare-earth mining and milling be eventually considered. This has the potential to reduce costs.
	2021	All	Re-formatted module consistent with revised approach to release of the AFC-CBR and escalated cost estimates from year of technical basis to escalated year 2020. Cost estimates are in US dollars ($) of year 2020.

Page intentionally left blank

ACKNOWLEDGEMENT

This latest version of the Module A2 Thorium Mining and Milling is the result of the cumulative effort of many authors that have contributed to the Advanced Fuel Cycle Cost Basis Report (AFC-CBR). It is not possible to identify and acknowledge all those contributions to the AFC-CBR and this module. All the authors, including the four primary authors, fifteen contributing authors, the twelve contributors acknowledged, and the many other unacknowledged contributors in the 2017 version of the report may have contributed various amounts to the development and writing of this module prior to this current revision. Unfortunately, there is not a consolidated history that allows us to properly acknowledge those that built the foundation that was updated and revised in this latest revision.

This update reformats previous work to the current format for rerelease of the entire report as individual modules so there is no primary technical developer or lead author. J. Hansen (INL) and E. Hoffman (ANL) can be contacted with any questions regarding this document.

jason.hansen@inl.gov; ehoffman@anl.gov

Suggested Citation:

DOE-NE Systems Analysis & Integration Campaign, *Advanced Fuel Cycle Cost Basis Report: Module A2 Thorium Mining and Milling*. Idaho Falls: Idaho National Laboratory, 2021.

Page intentionally left blank

CONTENTS

ACKNOWLEDGEMENT iv

ACRONYMS viii

A2-1. SHORT DESCRIPTION OF METHODOLOGY USED FOR ESTABLISHMENT OF MOST RECENT COST BASIS AND UNDERLYING RATIONALE 1

A2-2. BASIC INFORMATION 1

A2-3. FUNCTIONAL AND OPERATIONAL DESCRIPTION 3
- A2-3.1. General 3
- A2-3.2. Extraction Techniques 4

A2-4. PICTURES AND DIAGRAMS 6

A2-5. MODULE INTERFACES 7

A2-6. SCALING CONSIDERATIONS 8

A2-7. COST BASES, ASSUMPTIONS, AND DATA SOURCES 8
- A2-7.1. Definition of Thorium Reserves 8
- A2-7.2. World Reserves of Thorium 9
- A2-7.3. Domestic Resources 10
- A2-7.4. Market Price for Thorium 12
- A2-7.5. Secondary Supplies 13
- A2-7.6. Consumption and Primary Supplies 13

A2-8. DATA LIMITATIONS 15

A2-9. COST SUMMARIES 15
- A2-9.1. Thorium Production Cost and Price 17

A2-10. SENSITIVITY AND UNCERTAINTY ANALYSES 19

A2-11. REFERENCES 22

FIGURES

Figure A2.1 Flowsheet for monazite isolation (IAEA 2005). 6

Figure A2.2 Flowsheet for thorium oxalate production from monazite (IAEA 2005). 7

Figure A2.3 Location of prospected thorium deposits in the United States (USGS 2009). 12

Figure A2.4 Thorium unit value, world mass-weighted average, 1952 to present, data in 1998 U.S. dollars (USGS 2008). 13

Figure A2.5 World thorium consumption, 1952 to present (USGS 2008). 14

Figure A2.6 World primary thorium production (USGS 2008). 15

Figure A2.7 Upper bound (purple), most probable (red), and lower bound (blue) uranium price forecasts obtained from USGS mineral price model data. 17

Figure A2.8 Module A2: Thorium mining and milling estimated cost frequency and cumulative distributions. 19

Figure A2.9 Annual mass flow chart for the once-through (Galperin, Radkowsky, Todosow 1999) concept in a 3400 MWt PWR. 20

Figure A2.10 India’s three-stage path to a closed, breeding thorium cycle (IAEA 2005). 21

TABLES

Table A2.1 Commercial and experimental reactors loading thorium or U-233 fuel (WNA 2009). 2

Table A2.2 Crustal abundance (grams/tonne) of selected elements. 3

Table A2.3 Major radiologically active wastes arising from production of 1 tTh from monazite (Data from Schapira 1999). 5

Table A2.4 Known world thorium resources by deposit type. 9

Table A2.5 Known world thorium resources recoverable at less than $80/kgTh. 9

Table A2.6 Distribution of identified resources of uranium and thorium. 10

Table A2.7 Estimated reserves in selected major thorium deposits in the United States (data source: Van Gosen et al. 2009). 11

Table A2.8 Average domestic thorium compound prices as reported by the U.S. Geological Survey. 12

Table A2.9 “What-it-takes” (WIT) Table (2012$). [Note: Table A2.13 gives the WIT values for the 2021 update] 16

Table A2.10 Thorium cost used in previous thorium fuel cycle studies. 16

Table A2.11 Cost summary table, 2012 $. [Note: these differ from those in Table A2.9 and are based on the same type of analysis as uranium. The range below is inclusive of the values in Table A2.9.] 18

Table A2.12 Cost summary table escalated to 2015 $. 18

Table A2.13 Module A2: Thorium Mining and Milling Cost summary table escalated to 2020$. [Note: factor of 1.19 used to escalate from 2009$] 18

ACRONYMS

AHWRs	advanced heavy water reactors
ANL	Argonne National Laboratory
AVR	Atom Versuchs Reaktor
BWR	Lingen boiling water reactor
DOE	U.S. Department of Energy
DOE-EIA	U.S. Department of Energy-Energy Information Administration
EAR-I	Estimated Additional Resources Category I
EAR-II	Estimated Additional Resources Category II
EU	enriched uranium
FBTR	Fast Breeder Test Reactor
IAEA	International Atomic Energy Agency
INL	Idaho National Laboratory
IREL	Indian Rare Earths Limited
LWRs	light-water reactors
MK	Manavalakurichi
MSR	Molten Salt Reactor
MSRE	Molten Salt Reactor Experiment
NEA	Nuclear Energy Agency
NPPs	nuclear power plants
OECD	Organization for Economic Cooperation and Development
OSCOM	Orissa Sands Complex
PHWRs	Kakrapar pressurized heavy water reactors
PWR	Pressurized Water Reactor
R&D	research and development
RAR	Reasonably Assured Resources
REE	rare earth element
REs	rare earth elements
THTR	Thorium High Temperature Reactor
USGS	U.S. Geological Survey
WIT	What-it-takes

Page intentionally left blank

Module A2
Thorium Mining and Milling

A2-1. SHORT DESCRIPTION OF METHODOLOGY USED FOR ESTABLISHMENT OF MOST RECENT COST BASIS AND UNDERLYING RATIONALE

- **Constant $ base year 2020 for this FY21 update.**
- **Nature of this FY21 Module update from previous AFC-CBRs:** Escalation only.
- **Estimating Methodology for latest technical update (2009) from which this FY21 update was escalated:** The analytical methods for the 2009 Thorium Mining and Milling unit costs/prices are the same as for Module A1 (Uranium Mining and Milling). As with Uranium Mining and Milling (A1) the Thorium costing methodology was augmented in the 2012 version by a different methodology which basically supported the results of the 2009 analysis. Cost/Pricing analysis methodology is based on analysis of historical data on other commodity metals which are mined and milled. Escalation of 19% from 2009 to 2020 is utilized to establish the FY21 cost ranges. The escalation factor of 1.193 is calculated from the recently updated table in Chapter 8, "Escalation Considerations," of the Main Report.

A2-2. BASIC INFORMATION

This module covers the factors involving extraction of thorium from the earth through production of thorium concentrate in one of the three forms in which it is stored: oxide, oxalate, and nitrate. It also provides a brief review of the past and present applications of thorium for nuclear power production. Apart from trace quantities of the alpha-emitting Th-228 ($T_{1/2}$=1.91 yr) decay product of Th-232, thorium found in nature consists of only one isotope, Th-232. This species has a half-life of over 14 billion years and is not fissile by thermal neutrons. Its fission threshold is rather high (ca. 700 keV) and its fission cross section does not exceed 0.1 barn over most of the range of neutron kinetic energies relevant to even fast-spectrum critical reactors. Instead, thorium is of interest because it breeds the attractive thermal fissile species U-233 via a neutron capture reaction followed by two beta decays:

$$^{232}_{90}Th(n,\gamma)^{233}_{90}Th \xrightarrow[T_{1/2}=22\ \text{min}]{\beta^-} {}^{233}_{91}Pa \xrightarrow[T_{1/2}=27\ d]{\beta^-} {}^{233}_{92}U. \tag{1}$$

Thorium fuel cycles have attracted interest for their potential to ameliorate resource sustainability and mitigate waste management concerns, as compared to the once-through uranium cycle. The potential of the thorium cycle to benefit long-term waste management arises from the relatively benign actinide content of thorium fuel at discharge. Plutonium and transuranic production in particular is greatly reduced as the activation products of Th-232 must undergo several neutron captures to form even the lightest long-lived transuranic, Np-237. As an example, one proposal for employing thorium in light-water reactors (LWRs) reduces plutonium production by a factor of 6–7 compared to an energy equivalent of U-235/U-238 fuel in the same reactor (Galperin, Radkowsky, Todosow 1999; also see Section A2-7).

All designs that utilize thorium in critical reactors must rely upon a more readily fissionable "seed" or "driver" fuel to provide the surplus neutrons needed to initiate U-233 breeding. To maximize U-233 production, thorium is often employed as a matrix material in driver fuel elements to promote in-situ breeding as well as in a breeding blanket. Historically U-235-enriched fuel has been used as the driver, although plutonium with other transuranics could also serve; in a mature closed thorium fuel cycle, sufficient excess U-233 is bred to serve as seed material for startup of new reactors. Indeed, in several respects (per-fission neutron yield, capture-to-fission ratio) U-233 is superior to U-235, both as a reactor fuel and as a candidate for weaponization. Some fuel cycle proposals blend U-238 with thorium to reduce the enrichment levels in order to gain a non-proliferation benefit. The resultant improvement in the intrinsic proliferation resistance comes at the expense of increased production of Pu-239 and other activation products derived from U-238.

Thorium use has been demonstrated in all major types of power producing reactors. Table A2.1 highlights noteworthy operational campaigns; several of which involved commercial power production. At present, India maintains the most aggressive thorium fuel cycle research and development (R&D) program, continue to load thorium in both commercial and research reactors. The Indian program has also demonstrated a substantially complete thorium fuel cycle by loading U-233 recovered from a breeder (the Fast Breeder Test Reactor (FBTR) as the primary driver fuel in another reactor (KAMINI and other research reactors). Table A2.1 shows that outside of India, large-scale utilization of thorium in power and test reactors ceased in the 1980s. The decline in interest in the thorium fuel cycle during this decade proceeded in tandem with a sharp and sustained drop in uranium prices and global slowdown in the construction of new nuclear power plants (NPPs).

Table A2.1 Commercial and experimental reactors loading thorium or U-233 fuel (WNA 2009).

Reactor	Location/Period of Operation	Comments
Shippingport, 100 MWe	USA, 1977–1982	Pressurized water reacorit (PWR) in operation from 1957; Th loaded 1977–1982 in seed-blanket array (ThO_2 – $^{233}UO_2$); successful demonstration of breeding in an LWR
Atom Versuchs Reaktor (AVR), 15 MWe	Germany, 1967–1988	He cooled, graphite moderated pebble bed, HEU-Th fuel (1,360 kg Th used over reactor lifetime, some fuel reached 150 MWd/kg burnup)
Dragon, 20 MWt	UK, 1964–1973	Utilized 10:1 Th:HEU converter fuel elements designed for 6-year residence time
Peach Bottom 1, 40 MWe	USA, 1967–1974	Helium-cooled graphite moderated oxide/dicarbide fuel
Thorium High Temperature Reactor (THTR), 300 MWe	Germany, 1983–1989	Helium-cooled, graphite moderated pebble bed, HEU-Th fuel
Fort St. Vrain, 330 MWe	USA, 1976–1989	Helium-cooled, graphite moderated, prismatic HEU-Th fuel
Kakrapar pressurized heavy water reactors (PHWRs), 220 MWe	India	Thorium used for power profile flattening in initial cores
Lingen boiling water reactor (BWR), 60 MWe	Germany	Limited in-core testing of Th/Pu fuel elements
KAMINI, 30 kWt	India, 1996–Present	Loaded with Al-^{233}U driver and Th blanket fuel; Other research reactors in India have also loaded Th-bearing fuel

Fast Breeder Test Reactor, 40 MWt	India, 1985–Present	Liquid metal fast breeder based on French “Rapsodie” design: Pu/UC driver, ThO_2 blanket
Molten Salt Reactor Experiment (MSRE), 7.4 MWt	USA, 1965–1969	Operated with $^{233}UF_4$-FLiBe fuel; MSRE was an investigation of the “driver” portion of a thorium-based molten salt fueled breeder

A2-3. FUNCTIONAL AND OPERATIONAL DESCRIPTION

A2-3.1. General

Thorium is widely distributed throughout the crust of the earth. Table A2.2 shows some typical concentrations; roughly three times more abundant than uranium, thorium is the 39-most common of the 78 crustal elements (Herring 2004). The ability to extract the thorium in a practical and cost-effective manner depends on the relative grade of the ore to be mined (i.e., the percentage of thorium in the ore body), the type of formation in which it resides, and the location. An ore body is, by definition, an occurrence of mineralization from which the metal is economically recoverable. It is therefore relative to both costs of extraction and market prices.

Table A2.2 Crustal abundance (grams/tonne) of selected elements.

Element	Grams/tonne
Gold	0.004
Silver	0.07
Tungsten	1.5
Molybdenum	1.5
Uranium	2.8
Thorium	7.2
Lead	13
Copper	55
Zinc	70
Iron	50,000

Phosphates, silicates, carbonates, and oxides of thorium are all found in nature. As it often associates with alkaline igneous rocks, thorium is commonly concentrated together with rare earth elements (REs), titanium, niobium, zirconium and uranium that exhibit similar behavior. Hence, ore bodies will often contain both thorium and uranium, although it is usually the case that only one of the two is present in economically viable concentrations.[a] As will be discussed later, the geographic distribution of known thorium resources does not align strongly with that of uranium resources.

Most of the thorium in ore bodies suitable for large-scale near-term extraction is found as $ThPO_4$ in the phosphate mineral monazite. The ThO_2 content of monazite concentrate ranges from 3% to 15%. Rare earth oxides constitute about 50% of typical monazite, with the dominant rare earth constituents being cerium, lanthanum, and yttrium. In most cases, monazite also contains a few tenths of 1% uranium, but zirconium and titanium are more often present at economically attractive concentrations. Monazite can be

a. There are exceptions: for example, monazite containing 11.3 w/o thorium and 15.6 w/o uranium concentrates has been found in Italy (Schapira 1999).

a notable constituent of alluvial formations, in particular beach sands: beach and inland placers of monazite account for around 30% of reported thorium reserves. Beach deposits containing economically attractive monazite concentrations are relatively common because offshore wave action will transport light minerals more readily than monazite. If the geographic configuration of a coastline and offshore currents are favorable, local wave, and tidal phenomena can concentrate monazite and other heavy minerals. Favorable beach sand concentrate in India may contain 0.5–2.0 weight percent (w/o) monazite. Sand concentrate from Florida in the U.S. has been found to yield 0.05 w/o monazite, a concentration that is still considered sufficiently favorable to warrant inclusion in the domestic thorium resource base (Schapira 1999).

Resource estimates of this type are affected by the value of other minerals that may be co-extracted from the same deposit. In fact, much historical thorium production was derived from milling of monazite for its rare earth content. As of 2009, however, monazite is not being milled in the United States; even at mine sites where it is present in the ore body (Hedrick 2007 and 2009).

Other formations may also give rise to suitable thorium deposits. For instance, thorium is produced, but in large it is not refined as an undesired by-product of carbonate ore mining. The thorium resource base in carbonates is large, but grades tend to be low: typically 0.5% versus 3–15% in monazite or higher in some vein-type deposits. The United States is unusual in that its most appealing deposits are vein-type silicate formations harboring thorite, $ThSiO_4$. Section A2-4 will expand upon the domestic resource picture, but monazite extraction will likely continue to dominate the short-term world supply picture. Mining techniques such as the monazite technique depicted below will be impacted by the difficulty in reaching the ore, the grade, and the amount of secondary waste to be generated.

A2-3.2. Extraction Techniques

Commercial scale monazite production began in the 1950s. Its mining process is of the open pit type: dredging is employed for shallow offshore or riverine collection of monazite sands, while bulldozers and other earth-moving equipment suffice for onshore formations such as dunes. Separation of monazite from overburden is simplified by differences in density, electrical conductivity, and magnetic properties of monazite as compared to other constituents. (See Figure A2.1 for a flowchart depicting the steps taken to isolate monazite.)

An aqueous process is employed to mill thorium from monazite. In India, where most of the world's monazite is currently processed, the mineral slurry is first dissolved in a basic (NaOH) medium. The resultant solution monazite is subjected to a series of extraction processes, as shown in Figure A2.2. At present, the final product of the Indian process is thorium oxalate, $Th(C_2O_4)_2 \cdot 2H_2O$, at 99% purity. This compound is sufficiently stable to be suitable for long-term storage in concrete silos. The oxalate decomposes to ThO_2 when heated (calcined) to 300–400°C. A portion of the Indian production is converted to "gaslamp mantle grade" thorium nitrate. At the Indian plants, around 1,000–10,000 tons of feed yields 1 tonne of thorium metal. Recovery efficiencies are presently approximately 90% (Schapira 1999).

Overburden haulage in this process is less than that of standard—underground or open-pit—uranium extraction techniques and radioactive waste by-product production is estimated to be two orders of magnitude less than is the case for production of analogous amount of uranium (IAEA 2005). Effluents from tailings and milling remain a concern. The thorium decay chain also has a gaseous member, Rn-220 (half life ($T_{1/2}$) = 56 s), although its content in secular equilibrium in the decay chain is several orders of magnitude smaller than that of the U-238 daughter Rn-222 ($T_{1/2}$ = 3.82 d). In addition longest-lived daughter of the Th-232 decay chain, Ra-228 ($T_{1/2}$=5.7 year), must be compared to $T_{1/2}$=77,000-year Th-230 from the U-238 chain. Hence tailings pile management and public health protection from milling operations is simplified in some respects, though in practice sufficient uranium might be present in the ore body for no practical gain to be observed. While inhalation of Rn-220 would lead to a higher radiological impact, its decay during the atmospheric dispersion process implies that its concentration at a postulated mill site boundary would be lower than for a uranium mill of equivalent capacity. (Schapira 1999)

The volume of radioactive wastes requiring long-term storage has been estimated at 0.4 m^3/tTh (i.e., one 75-cm-diameter × 90-cm-high barrel (Schapira 1999). This waste arises because radium is extracted with other waste products during rare earth purification steps. Since Ra-228 has a half-life of 5.7 years and its descendants are all shorter-lived, in principle the solid waste would be suitable for permanent disposal within a few decades. In practice, the presence of small amounts of longer-lived Ra-226 ($T_{1/2}$=1600 yr), a U-238 decay product, might preclude this option. Additional byproducts include about 1 tonne per tonne Th of low-level and 3–6 tonnes per tonne Th of medium-level solid wastes suitable for shallow land burial. Table A2.3 summarizes the major radioactive wastes arising from extraction from a typical Indian deposit and processing of monazite ore to yield 1 tonne Th.

Table A2.3 Major radiologically active wastes arising from production of 1 tTh from monazite (Data from Schapira 1999).

Waste form	Mass [tonne / tonne Th metal]	Storage/disposal strategy
Solid, Ra-228-bearing waste arising from rare earth purification	0.47 (0.4 m^3/tonneTh)	Reinforced cement concrete barrels; long-term storage in underground trenches
Medium-level liquid and acid-leached solid from solid-liquid separation of thorium concentrate	~3–6 depending on desired Th purity	Suitable for ground disposal
Low-level solid from other steps in process	~1	Suitable for shallow ground disposal.

A2-4. PICTURES AND DIAGRAMS

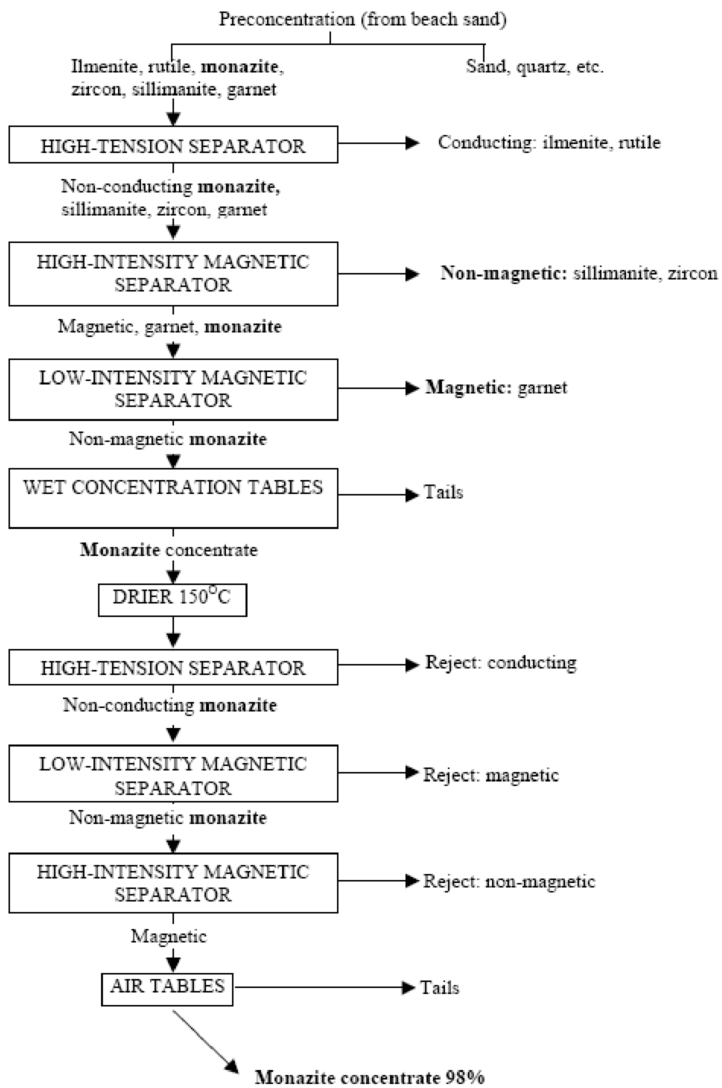

Figure A2.1 Flowsheet for monazite isolation (IAEA 2005).

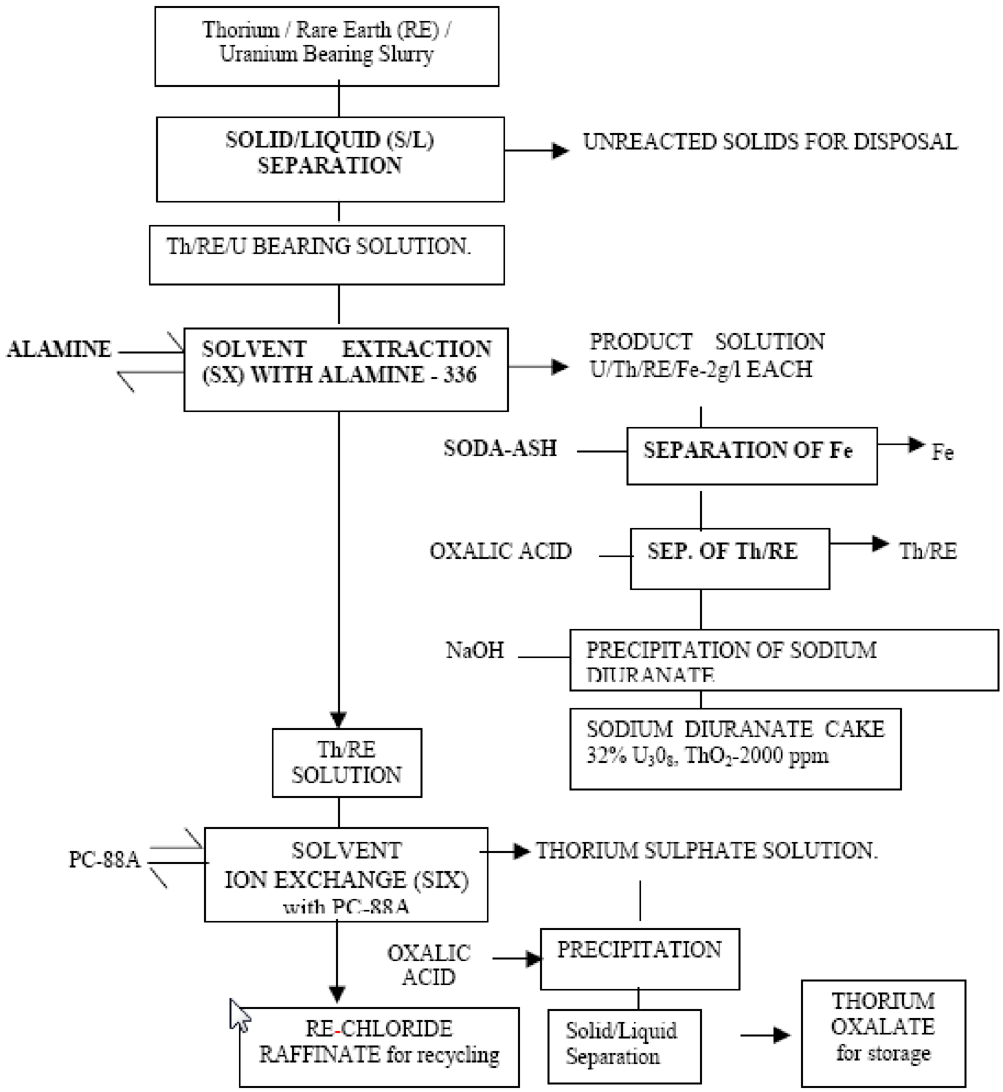

Figure A2.2 Flowsheet for thorium oxalate production from monazite (IAEA 2005).

A2-5. MODULE INTERFACES

The product of Module A2 is greatly influenced by the requirements for Module D1, Fabrication of Contact-handled Fuels, which defines overall demand. However, relative to specific demand, there are other factors outside of the defined modules that have influence on this module. In particular, the requirements for Module D1 can be affected by the driver or seed fuel providing the fissile support for the thorium-bearing fuel. Note that there is no enrichment in thorium-based fuel cycles unless enriched uranium (EU) is in use as a driver fuel. Therefore, Module A2 interfaces with Modules B and C1 in this context only.

A2-6. SCALING CONSIDERATIONS

Scaling factors are not specifically applicable. Size and cost of establishing a new mine will depend on many factors and are not generally scalable unless conditions would be nearly identical to another mining opportunity including type of mining method, location, and type of ore body, thickness of seam, etc.

A2-7. COST BASES, ASSUMPTIONS, AND DATA SOURCES

The cost basis for thorium depends on a number of factors impacting supply and demand. Availability, at a given cost, drives the specific supply to meet demand for new product. This demand may be heavily impacted by the cost of uranium, which is addressed in Module A1. The following discussions highlight the key factors relative to the actual supply and demand for newly produced thorium.

A2-7.1. Definition of Thorium Reserves

Availability of supply is evaluated using the accepted systematic convention of reporting reserves as established by a joint Organization for Economic Cooperation and Development/Nuclear Energy Agency-International Atomic Energy Agency (OECD/NEA-IAEA) expert group and as adapted by U.S. Department of Energy-Energy Information Administration (DOE-EIA). The various categories of reserves indicate both the confidence level that given amounts of reserves will exist as well as the difficulty in making that thorium available for use. These indications are expressed in an estimated cost to reclaim and utilize the reserves with reasonably established methods. Extensive analyses of factors affecting the uranium market are performed regularly and published in a biennial report by OECD/NEA-IAEA known as the *Red Book* (OECD 2008). Until 1982, the *Red Book* offered a similar depth of analysis for thorium; subsequently, however, all but the summary information was dropped. The de-emphasis of thorium in the *Red Book* paralleled a general decline in interest in thorium as a commodity, but nonetheless the *Red Book* continues to provide limited estimates of thorium reserves.

The definitions of the conventional resource categories, as established by the OECD/NEA-IAEA, are the same as those adopted for uranium, with two exceptions: Speculative and Unconventional Resources are not tabulated for thorium. The resource categories are listed below, in order of decreasing confidence in the deposit size and extraction cost.

Reasonably Assured Resources (RAR) refer to thorium that occurs in known mineral deposits of delineated size, grade, and configuration such that the quantities that could be recovered within the given production cost ranges with currently proven mining and processing technology can be specified. Estimates of tonnage and grade are based on specific sample data and measurements of the deposits and on knowledge of deposit characteristics. RAR have a high assurance of existence.

Estimated Additional Resources Category I (EAR-I) refers to thorium in addition to RAR that is inferred to occur, mostly on the basis of direct geological evidence, in extensions of well-explored deposits or in deposits in which geological continuity has been established, and where specific data, including measurements of the deposits and knowledge of the deposits' characteristics, are considered to be inadequate to classify the resource as RAR. Estimates of tonnage, grade, and cost of further delineation and recovery are based on such sampling as is available and on knowledge of the deposit characteristics as determined in the best known parts of the deposit or in similar deposits. Less reliance can be placed on the estimates in this category than on those for RAR.

Estimated Additional Resources Category II (EAR-II) refers to thorium in addition to EAR-I that is expected to occur in deposits for which the evidence is mainly indirect and which are believed to exist in well-defined geological trends or areas of mineralization with known deposits. Estimates of tonnage, grade, and cost of discovery, delineation, and recovery are based primarily on knowledge of deposit characteristics in known deposits within the respective trends or areas and on such sampling, geological, geophysical, or geochemical evidence as may be available. Less reliance can be placed on the estimates in this category than on those for EAR-I.

A2-7.2. World Reserves of Thorium

The IAEA *Red Book 2007* estimates world thorium resources to be 6.08 million metric tons. Table A2.4 provides the distribution of resources by deposit type. Monazite-bearing placer deposits can have thorium grades of 10% or more and are likely to be among the first resources exploited if thorium production expands.

Table A2.4 Known world thorium resources by deposit type.

Deposit Type	Amount (1000 tTh)
Carbonatite	1,900
Placer (alluvial)	1,500
Vein-type	1,300
Alkaline Rocks	1,120
Other	258
Total	**6,078**
"t" is metric tonne.	

In contravention to the practice followed in its uranium estimate, wherein the resource is classified into four extraction cost categories as well as the confidence levels described above, the *Red Book* provides only two cost categories for thorium. These are: extractable at a cost of \$80/kgTh or less (4.36 million metric tons) and extractable at greater than \$80/kgTh (1.72 million metric tons). Table A2.5 shows the distribution by confidence level of resources extractable at \$80/kgTh or less (OECD 2008).

Table A2.5 Known world thorium resources recoverable at less than \$80/kgTh.

Resource Category	Amount (1000 tTh)
Reasonably Assured Resources	1,173
Inferred Resources	1,400
Prognosticated Resources	1,787–1,887*
Total	**4,360**
"t" is metric tonne. * The OECD estimate of Prognosticated Resources in Turkey is 400–500 tTh, accounting for the range seen above.	

Table A2.6 shows the geographic distribution of thorium reserves as derived from OECD/NEA-IAEA data. The distribution of uranium is provided for comparison; the distinct geological characteristics of minerals bearing the two elements give rise to wide variance in locations where the elements are sufficiently concentrated to be economically viable for extraction. Note that the thorium reserves of India are six times larger than its uranium reserves; supply-security has been instrumental in fostering the emphasis on thorium in the Indian fuel cycle R&D program.

Table A2.6 Distribution of identified resources of uranium and thorium.

Country	Percentage of World Thorium[a]	Percentage of World Uranium[a]
Australia	18%	28%
USA	16%	3%
Turkey	13%	<2%
Brazil	12%	6%
India	12%	<2%
Venezuela	12%	<2%
Norway	5%	<2%
Egypt	4%	<2%
Russian Fed.	3%	5%
Canada	2%	12%
Others	~3%	~36%

a. Reasonably Assured Resources plus Inferred Resources to $80/kgTh.

It is interesting to note that, although thorium is considerably more abundant than uranium, the *Red Book* identified thorium resources, 4,360 thousand tTh, are less than the identified uranium resources, 5,469 thousand tU. This should not be taken to imply that the potential supply of economically viable thorium is smaller than that of uranium. The figures reported in the *Red Book* are supplied to the OECD/NEA-IAEA by member countries and are tied to the thoroughness of prospecting activities in the individual nations. Since demand for thorium is low, it is only lightly prospected and the identified resource base would assuredly increase if demand were revived. As an example, the identified uranium resource base reported in the *Red Book* increased from 3,400 thousand tU in the original 1965 *Red Book* to its current value of 5,469 thousand tU even, as about 2,000 thousand tU were extracted from the ground.

Limited thorium prospecting activities continue in several countries. Prospecting is most intensive in India where a mature thorium production chain already exists. Exploration has also been reported in Canada and the United States; in the U.S., Thorium Energy, Inc., contracted Idaho Engineering and Geology, Inc., to further quantify the extent of its thorium holdings in the Lemhi Pass area of Idaho and Montana. In a report submitted to the U.S. Geological Survey (USGS), the investigators indicated that the Th deposits in the Lemhi Pass area may be considerably larger than the USGS values cited below (Gillerman 2008).

A2-7.3. Domestic Resources

The identified thorium resource base of the United States is the second largest in the world, after that of Australia. Table A2.7 shows the reserves associated with the largest known domestic deposits and Figure A2.3 maps the location of these deposits. Much of the identified thorium is contained in vein deposits; the Lemhi Pass mining district in Montana and Idaho is the largest of these with over 56,000 tTh of reserves and additional undiscovered resources estimated at over 100,000 tTh. Silicate (thorite) and phosphate (monazite) veins dominate in this region. Samples taken from the ten largest veins in the district indicated an average ore grade of 0.43 w/o ThO_2. The USGS estimates that the Wet Mountains region, in which thorite veins predominate, may also contain undiscovered resources of greater than 100,000 tTh. The thorium ore grade at Wet Mountains is similar to that of Lemhi Pass: the average ore grade of 201 samples taken from Wet Mountains was found to be 0.46 w/o ThO_2. (Van Gosen et al., 2009)

Domestic carbonate resources are also extensive. Thorium concentrations in carbonate deposits are typically low; the formations at Iron Hill, for instance, bear only 30–40 ppm Th. Yet this and other carbonatite formations are enriched in rare earth elements, as well as Ti, V, and Nb, so that Th production as a co-product may become economically appealing. Domestic placer deposits of monazite similar to those already being tapped in India also represent a considerable share of U.S. reserves. These alluvial monazite deposits are located in beach sands (Florida) as well as riparian environments in Idaho and the Carolina Piedmont. (Van Gosen et al. 2009)

There is currently no production of thorium in the United Sates. The limited domestic industrial demand for Th, averaging less than 10 t/yr from 1995 to the present, has been satisfied by imports or consumption of stockpiled material.

Table A2.7 Estimated reserves in selected major thorium deposits in the United States (data source: Van Gosen et al. 2009).

Name, location *(deposit type)*	Amount (tTh)
Lemhi Pass, Montana-Idaho *(vein)*	56,200
Wet Mountains, Colorado *(vein)*	51,100
Iron Hill, Colorado *(carbonate, vein)*	26,900
Florida beach placers *(placer)*	12,900
Idaho stream placers *(placer)*	8,000
Mountain Pass, California *(carbonate)*	7,800
North and South Carolina stream placers *(placer)*	4,200
Hall Mountain, Idaho *(vein)*	3,600

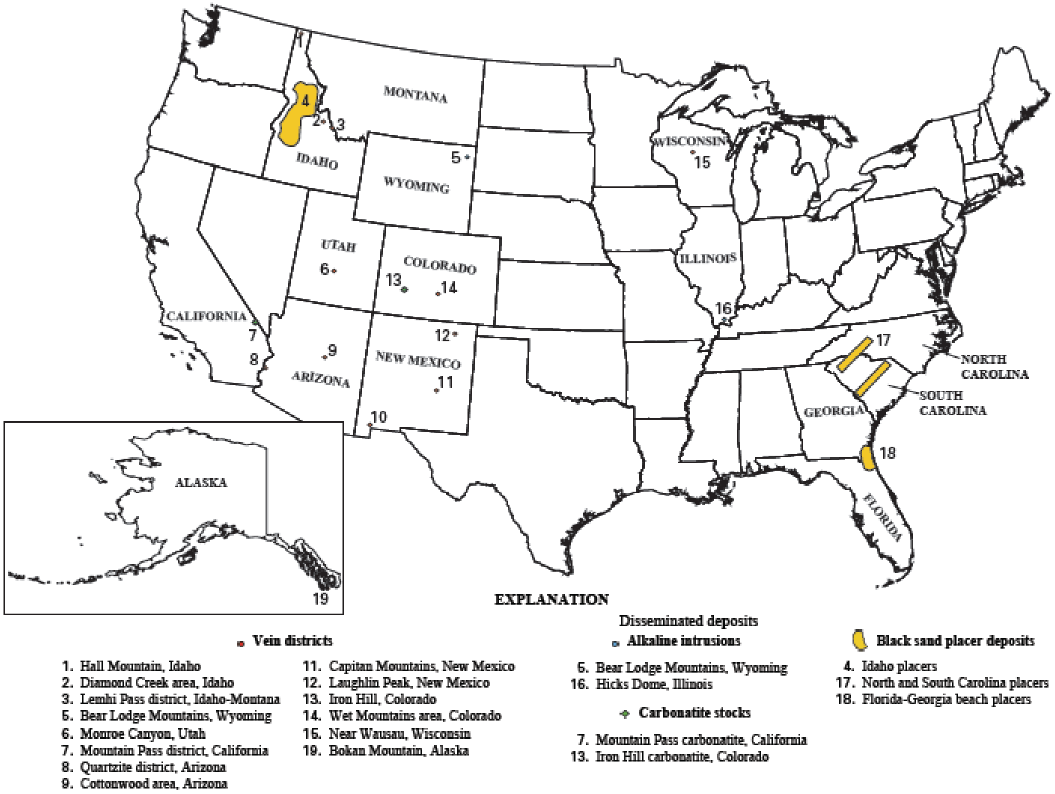

Figure A2.3 Location of prospected thorium deposits in the United States (USGS 2009).

A2-7.4. Market Price for Thorium

Due to its small size, the thorium industry is not associated with a well-developed commodity market of the type that has matured around the uranium resource. Therefore, such data as exists on recent thorium prices derived from individual transactions and evinces a great deal of variability. Table A2.8 shows that prices are highly dependent on product purity. This price disparity with product grade would be expected to decline if the industry expanded in scope and the demand for high-purity products increased.

Table A2.8 Average domestic thorium compound prices as reported by the U.S. Geological Survey.

	Mid 1990s prices (1996 USD, Hedrick 1997)	Mid 2000s prices (2008 USD, Hedrick 2009)
Nitrate, welding grade	\$5.46/kg $Th(NO_3)_4$	\$5.46/kg $Th(NO_3)_4$
Nitrate, mantle grade	\$22.10/kg $Th(NO_3)_4$	\$27.00/kg $Th(NO_3)_4$
Oxide, 99.0% purity	\$64.20/kg ThO_2	Not reported
Oxide, 99.9% purity	\$89.25/kg ThO_2	\$113.33/kg ThO_2
Oxide, 99.99% purity	\$107.15/kg ThO_2	\$164.35/kg ThO_2

The USGS also reports an imputed thorium price index, the so-called “unit value” index. This may be most relevant to nuclear energy applications of thorium as it is tied to the economic value of consumption of high-purity thorium oxide (97% purity before 1977, 99% between 1978 and 1994, and 99.9% from 1995 to the present). The data series is plotted in Figure A2.4; its volatility should be interpreted as a consequence of the small number of annual transactions rather than the action of market forces.

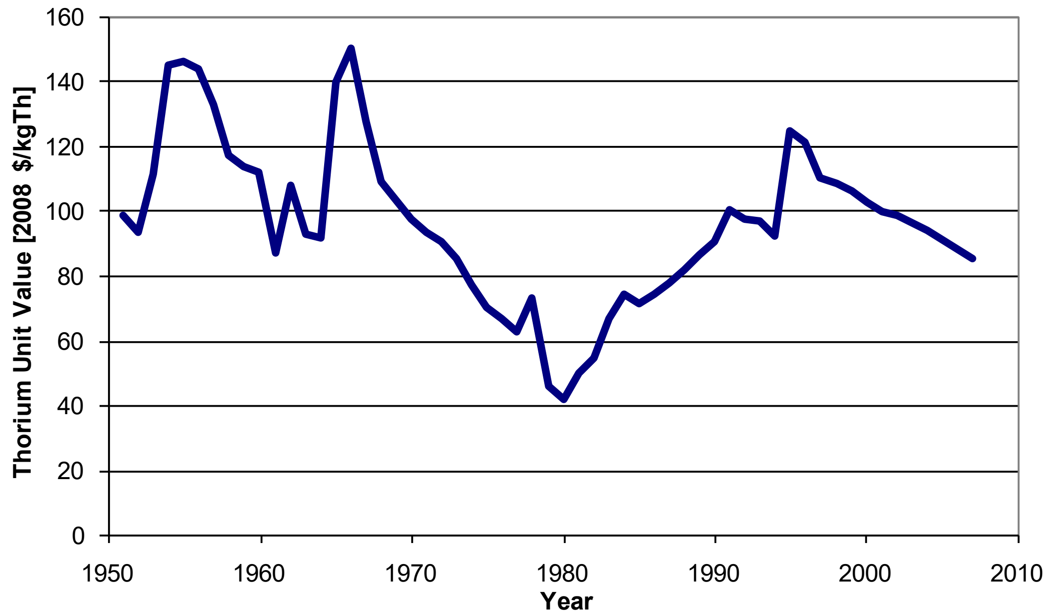

Figure A2.4 Thorium unit value, world mass-weighted average, 1952 to present, data in 1998 U.S. dollars (USGS 2008).

A noteworthy difference between a potential upper limit on thorium and uranium extraction costs arises from the relative concentrations of the two elements in seawater. Uranium is moderately soluble in water (3 ppb), so that its recovery from that host may ultimately become viable. The solubility of thorium is very low (0.05 ppb), so its extraction from seawater is not at all feasible.

A2-7.5. Secondary Supplies

By far the largest potential reservoir of easily accessible secondary thorium is tailings associated with milling operations where thorium was not taken up as a product. Approximately 25,000 $tThO_2$ are contained in residues resulting from the processing of monazite for rare earths recovery (Schapira 1999).

The U.S. Atomic Energy committee obtained several thousand metric tons of thorium nitrate in the 1950s and 1960s. The unused portion of this material was stored at the Defense National Stockpile Center depots in Maryland and Indiana. In the early 2000s, following a study that compared the costs of continuing to store the thorium, either as nitrate or in a more stable form, to the cost of disposal, the U.S. government decision to permanently dispose 3,200 metric tons of thorium by burying it at the Nevada Test Site. This operation, in which over 21,000 drums thorium nitrate were buried in pits sealed with over 20 feet of top cover, was completed in 2005 (Hermes and Terry 2007). This material is potentially retrievable.

A2-7.6. Consumption and Primary Supplies

Commercial use of thorium for incandescent lighting (ORAU 2009) applications (Welsbach mantles) began as early as 1884. Thorium has since found limited application in selected non-energy uses tied to its electron density and the very high melting point of its ceramic oxide compounds. Employment of thorium as a chemical catalyst, as well as in welding electrodes (where it improves arc stability as compared to tungsten-only electrodes) and high-temperature ceramics, has declined as non-radioactive substitutes have come into widespread use. Thorium nitrate has historically been employed as a thermoluminescent material in camping lantern mantles but has largely been supplanted in this role by yttrium oxide. The

USGS cites liability concerns, environmental monitoring regulations and disposal costs as forces driving industrial consumers toward acceptable non-radioactive substitutes to thorium (Kelly 2007).

Worldwide industrial consumption of thorium is therefore small and continues to decline. Apparent consumption, having averaged 50 t/yr from the mid 1970s through the early 1990s, dropped to around 10t/yr thereafter (Figure A2.5). These figures may do fully reflect thorium consumption in India where a small portion of primary thorium is converted to nitrate form for industrial use, but the remainder is added to a government-controlled stockpile. This stockpile—30,000 t of thorium concentrate—is being retained for use in its planned thorium-based fuel cycle (Kelly 2007).

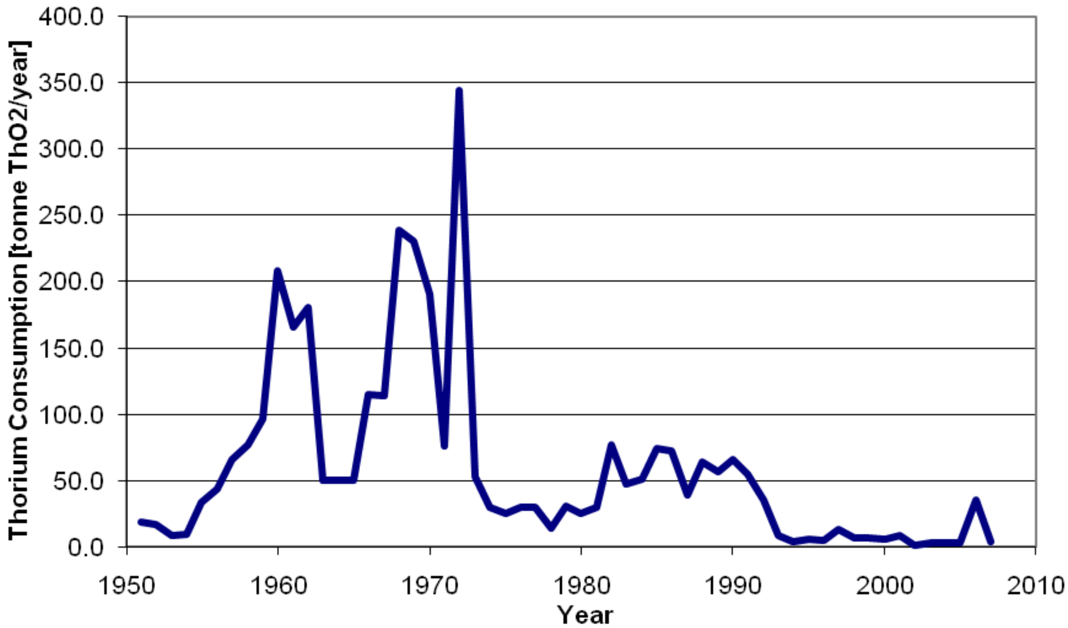

Figure A2.5 World thorium consumption, 1952 to present (USGS 2008).

No unified data set of world thorium production was produced after 1977 although it is known that thorium production declined sharply from the late 1970s. Indian Rare Earths Limited (IREL) is presently the largest producer of thorium through its rare earths production operations from beach sands at Chavara and Manavalakurichi (MK). MK produces around 3000 t/yr of monazite with a thorium content of approximately 200 t/yr. Indian output accounts for around 90% of world monazite production of around 6000 t/yr (IAEA 2006). The largest IREL thorium refinement facility, the Orissa Sands Complex (OSCOM), has a capacity of 240 t/yr $Th(NO_3)_4$ or 116 tTh/yr (IREL 2009). Outside of India, small amounts of thorium are produced only as by-product from monazite milling operations.

Figure A2.6 shows the primary thorium production data that is available. Note that production just between 1960 and 1977 substantially exceeded consumption from 1960 to the present. Production continues at the current time, notably in India; however, numerical data are not available. Instead, the dashed line illustrates a theoretical maximum thorium production rate of 450 t/yr. This figure was obtained by surmising that the full 6000 t/yr of monazite extracted annually (an average rate for 2005–2008, with an average thorium concentrate content of 7.5 w/o) were milled for thorium recovery. The true annual production is likely somewhat lower.

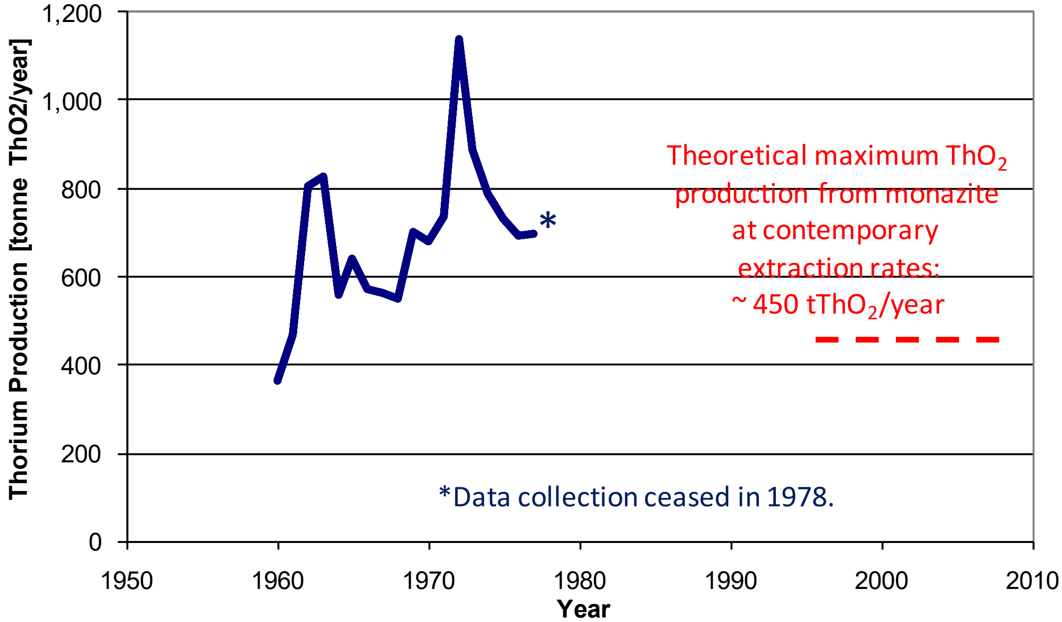

Figure A2.6 World primary thorium production (USGS 2008).

A2-8. DATA LIMITATIONS

Much of the data is based on speculation and intuitive evaluation of geologic data and speculation relative to the movement of future power markets versus demand. Many factors including actual cost of recovery, future regulatory impacts (both positive and negative), and especially the ultimate level of interest in thorium fuel cycles will affect the reliability of the information. The data best represent a "speculative supply" to an uncertain demand. As is the case with uranium and other minerals resources, it should be expected that a thorium industry will be susceptible to boom-bust cycles, shocks and other events that introduce both cyclical behavior and volatility in the market price. Yet the price of thorium in a mature industry would fluctuate in the vicinity of **the long-run marginal cost of its production. The estimate presented in this module is intended to reflect that cost.**

A2-9. COST SUMMARIES

The sole update to the thorium mining and milling module is to the what-it-takes table. In the December *2009 Cost Basis Report* (2009 CBR), the relative distribution of low, high and nominal thorium mining and milling prices followed those of uranium, although the values themselves were one-third lower than those for uranium. Please refer to the 2009 CBR for discussion of the basis for this estimate and a review of historical thorium price data and price estimates.

Since the uranium price distribution has changed (see Module A1), the thorium forecast will be adjusted to maintain consistency. Table A2.9 updates the what-it-takes table for thorium mining and milling. All costs are at two-thirds of the corresponding values presented in Module A1, rounded to the nearest $5/kg Th.

Table A2.9 "What-it-takes" (WIT) Table (2012$). [Note: Table A2.13 gives the WIT values for the 2021 update]

Low Cost	High Cost	Mode Cost
$45/ kg Th	$155/ kg Th	$75/ kg Th
2009 CBR Values:		
$20/kg Th	*$175/kg Th*	*$50/kg Th*

The price given above is for thorium as the oxalate, Th $(C_2O_4)_2 \bullet 2H_2O$. This is the forum of output by the Indian process, and the Indians are the largest producers at present. Thorium has also been shipped in oxide and nitrate forms.

No thorium is currently produced in the United States. Annual domestic consumption is miniscule: in 2011, less than 10 metric tonnes of thorium with a total value of $398,000 were purchased. The unit cost of these transactions averaged $68.6/kg Th [1]. Around the world, thorium is extracted from heavy-mineral sands as a constituent of the rare earth element (REE) bearing mineral monazite. Given low demand, the co-extracted thorium is generally not chemically isolated for marketing as a byproduct of REE operations but instead left in tailings and disposed.

The 2009 CBR estimate of thorium production costs assumes that thorium would be produced at scale as a major or sole product of mining and refining operations, as is the case for uranium. But it may prove that thorium requirements, even at the levels needed to support large-scale use of a thorium fuel cycle, can be satisfied solely through its production as a REE byproduct. Monazite generally contains 6 to 12% thorium oxide. 2011 world production of monazite concentrate was at least 6,410 metric tonnes (China, Indonesia and others may also possess monazite operations but did not report data) [1].

If byproduct production of thorium proves likely to be sufficient, reduction of the low and nominal cost estimates presented here would be justified. The new Th production cost estimates would be tied to the cost of isolating and refining thorium from acid or alkaline solutions during monazite cracking.

Assessments are ongoing of both the feasibility of meeting requirements solely from byproduct operations and the cost of the associated Th refining process. Their results will be addressed in the next update of the CBR.

Since there is no true market for thorium, investigators who have studied the economics of thorium-using fuel cycles have limited themselves ad hoc estimates of future thorium prices. No formal estimates of future thorium price dynamics or market behavior have been undertaken. Table A2.10 shows the thorium cost used in four system-level studies of thorium-based fuel cycles. These estimates all lie at or near the ceiling production cost for identified thorium resources quoted by the OECD/NEA-IAEA ($80/kgTh) and the prices quoted by the USGS for thorium of 99% or higher purity ($64–$164).

Table A2.10 Thorium cost used in previous thorium fuel cycle studies.

Source	Cost (U.S. $/kgTh)	Basis Year
(IAEA 2005)	50	2005
(Herring et al. 2001)	88.5	2000
(Bae, Kim 2005)	85	1994
(Wang 2003)	50	2003

It seems reasonable to postulate that $80/kgTh, the upper boundary of the OECD/NEA-IAEA production cost category for identified thorium resources, represents a reasonable near-term marginal production (mining plus milling) cost for Th as ThO_2. This may be thought of as a consensus estimate as it is in reasonable alignment with estimates from fuel cycle system analyses and USGS prices: the USGS-quoted prices for high-purity thorium are in fact somewhat higher than $80/kgTh, but this may be ascribed to the very small scale of the milling operations that support transactions on the order of less than 10 t/yr.

In Module A1, the marginal cost model presented in Section A1-6 was applied to provide a forecast of the evolution of the uranium resource production cost. Namely, it was proposed that future uranium price trends should not be expected to diverge from the experience of many other minerals over the past century. Using a statistical model derived from those mineral price histories, a very approximate projection of uranium price evolution over this century was presented. To do so, a starting point for the uranium price that roughly corresponds to a present-day marginal production cost was chosen. Beginning from that price in 2005, price evolutions corresponding to the mean and upper and lower confidence interval boundary values derived from 105 years of price data for other minerals were computed.

The thorium forecast depicted in Figure A2.7 follows this procedure for thorium but starts (in 2009) from a marginal cost of $80/kgTh. A time-averaged thorium price for this century, rounded to the nearest $5/kgTh, was computed for each of the three evolutions. These constitute the lower, nominal, and upper costs given in the What-It-Takes table.

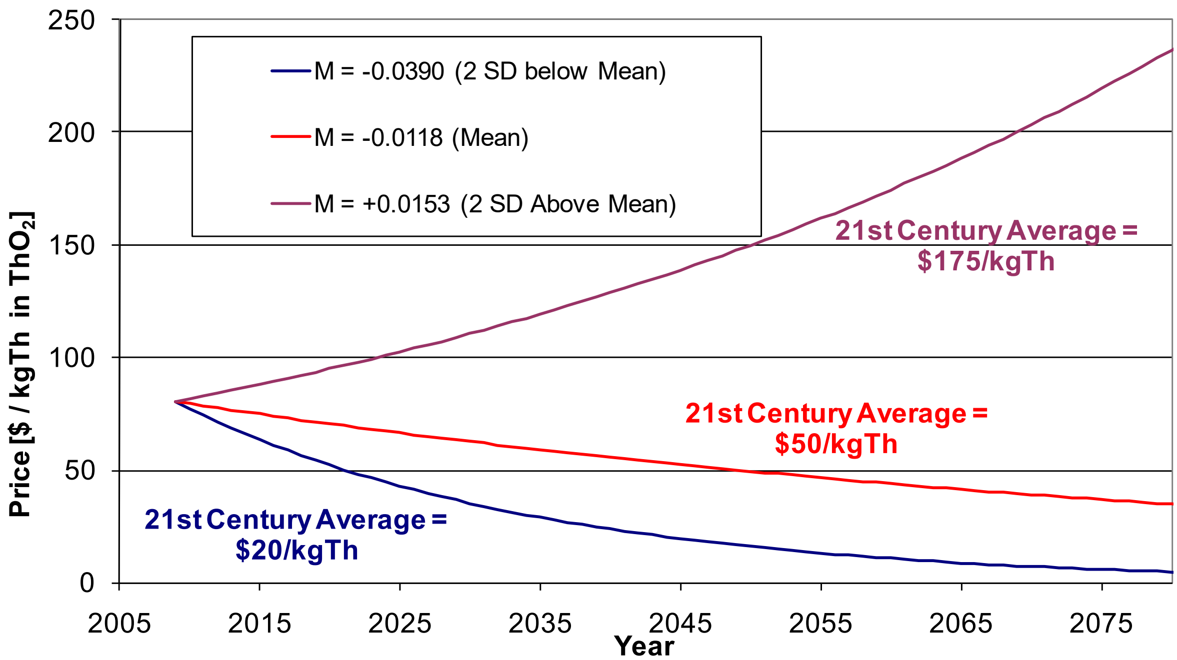

Figure A2.7 Upper bound (purple), most probable (red), and lower bound (blue) uranium price forecasts obtained from USGS mineral price model data.

A2-9.1. Thorium Production Cost and Price

The module cost information is summarized in the What-It-Takes (WIT) cost summary in Table A2.11. The summary shows the reference cost basis (constant year U.S. dollars), the reference basis cost contingency (if known), the cost analyst's judgment of the potential upsides (low end of cost range) and downsides (high end of cost range) based on references and qualitative factors, and selected nominal costs (judgment of the expected costs based on the references, contingency factors, upsides, and downsides).

These costs are subject to change and are updated as additional reference information is collected and evaluated, and as a result of sensitivity and uncertainty analysis. Refer to Section 2.6 in the main section of this report for additional details on the cost estimation approach used to construct the WIT table.

The triangular distribution based on the costs in the WIT table is shown in Figure A2.8. Note that the mean cost associated with this skewed distribution is $82/kgTh.

Table A2.11 Cost summary table, 2012 $. [Note: these differ from those in Table A2.9 and are based on the same type of analysis as uranium. The range below is inclusive of the values in Table A2.9.]

What-It-Takes (WIT) Table				
Reference Cost(s) Based on Reference Capacity	Reference Cost Contingency (+/- %)	Low Cost	High Cost	Mode Cost
$80/kgTh	NA	$20/kgTh	$175/kgTh	$50/kgTh
For Th as ThO_2 (99.9% purity)				

As with uranium mining and milling, throrium mining and milling costs (and ultimately prices) are subject to escalation. Table A2.12 below shows the year 2015$ costs.

Table A2.12 Cost summary table escalated to 2015 $.

	What-It-Takes (WIT) Table				
Reference Cost(s) Based on Reference Capacity	Reference Cost Contingency (+/- %)	Low Cost	Mode Cost	Mean Cost	High Cost
$84/kgTh	NA	$21/kgTh	$53/kgTh	$86/kgTh	$184/kgTh
For Th as ThO_2 (99.9% purity)					

Table A2.13 Module A2: Thorium Mining and Milling Cost summary table escalated to 2020$. [Note: factor of 1.19 used to escalate from 2009$]

	What-It-Takes (WIT) Table				
Reference Cost(s) Based on Reference Capacity	Reference Cost Contingency (+/- %)	Low Cost	Mode Cost	Mean Cost	High Cost
$100.2/kgTh	NA	$24.2/kgTh	$59.4/kgTh	$97.9/kgTh	$209.0/kgTh
For Th as ThO_2 (99.9% purity)					

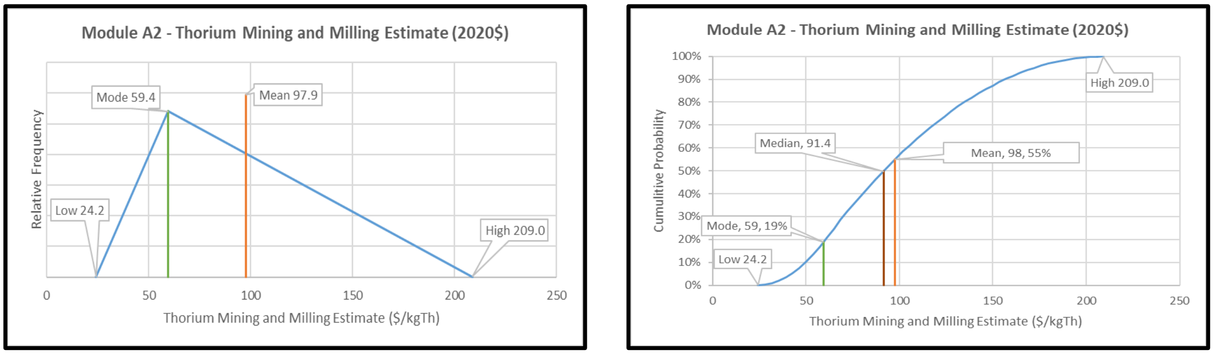

Figure A2.8 Module A2: Thorium mining and milling estimated cost frequency and cumulative distributions.

A2-10. SENSITIVITY AND UNCERTAINTY ANALYSES

Thorium Cost Sensitivity. Thorium-based fuel cycles are expected to be less sensitive to the cost of their resource than is the case for present-day uranium cycles. While the unit cost of both metals is of the same order, since natural thorium contains no fissile species thorium cycles invariably feature multiple recycle or at least extensive in-situ U-233 breeding. The once-through uranium cycle currently fissions less than 1% of mined uranium; a fully-closed breeding-based thorium cycle, like the analogous uranium cycle, would eventually offer complete utilization of the resource. Even thorium cycles suitable for once-through, for instance those featuring direct disposal of heterogeneous seed-blanket fuel assemblies, would be insensitive to the cost of the thorium resource. Radkowsky Thorium Fuel and similar concepts, for example, would result in the fission of 8–10% of the thorium blanket fuel (Galperin, Radkowsky, Todosow 1999). It must be noted that these cycles rely on the presence of an enriched uranium or plutonium (as Pu/U/ThO_2 MOX) seed, although overall resource utilization efficiency (MWd/kg(NU+Th)) is comparable to current practice. Figure A2.9 shows annualized mass flows for a 3400 MWt PWR operating under the Radkowsky concept. The plutonium discharge is reduced by a factor of approximately six as compared to an energy equivalent quantity of conventional LEU fuel. Similarly, large reductions are seen in trans-plutonium species, and the bred-in LEU is mixed in-situ with the existing blanket uranium so that the discharged uranium mixture falls below IAEA limits.

It is important to note that this once-through cycle does not offer a marked uranium resource sustainability benefit; its separative work requirement is in fact somewhat higher than for an energy-equivalent LEU-only cycle. A fully-closed, breeding-based thorium cycle is quite feasible if U-233 is recovered. The three-stage Indian strategy for transitioning to such a cycle is shown in Figure A2.10. Stage 1, which is ongoing, involves conventional LWRs and HWRs. Some thorium oxide fuel is loaded and serves to flatten power profiles, but the predominant fuel is uranium. In Stage 2, sodium-cooled fast breeder reactors with thorium blankets utilize plutonium recovered from the LWRs and HWRs as driver fuel. U-233 from the fast reactors starts up the advanced heavy water reactors (AHWRs) of Stage 3. These operate with a breeding ratio of greater than unity, so that the fast reactors can eventually be phased out once sufficient U-233 inventory is attained. Therefore, this cycle ultimately draws upon only the thorium resource.

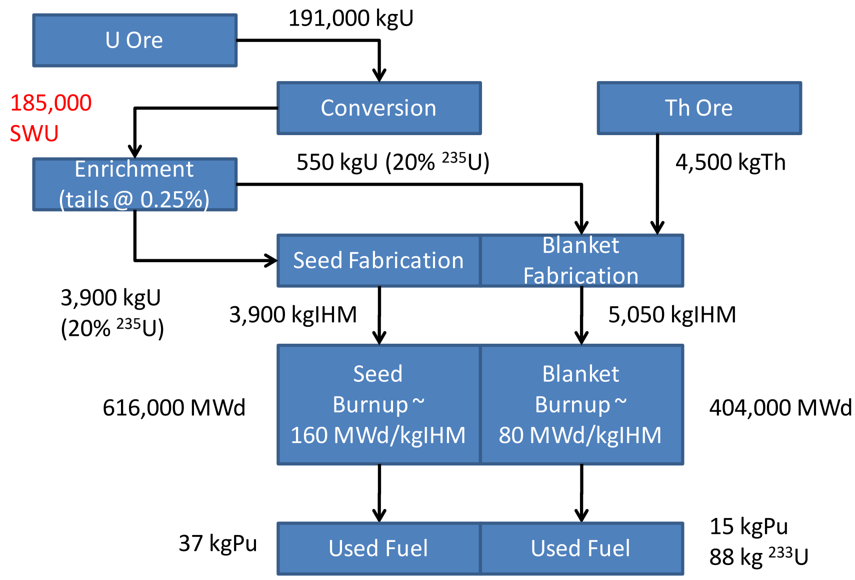

Figure A2.9 Annual mass flow chart for the once-through (Galperin, Radkowsky, Todosow 1999) concept in a 3400 MWt PWR.

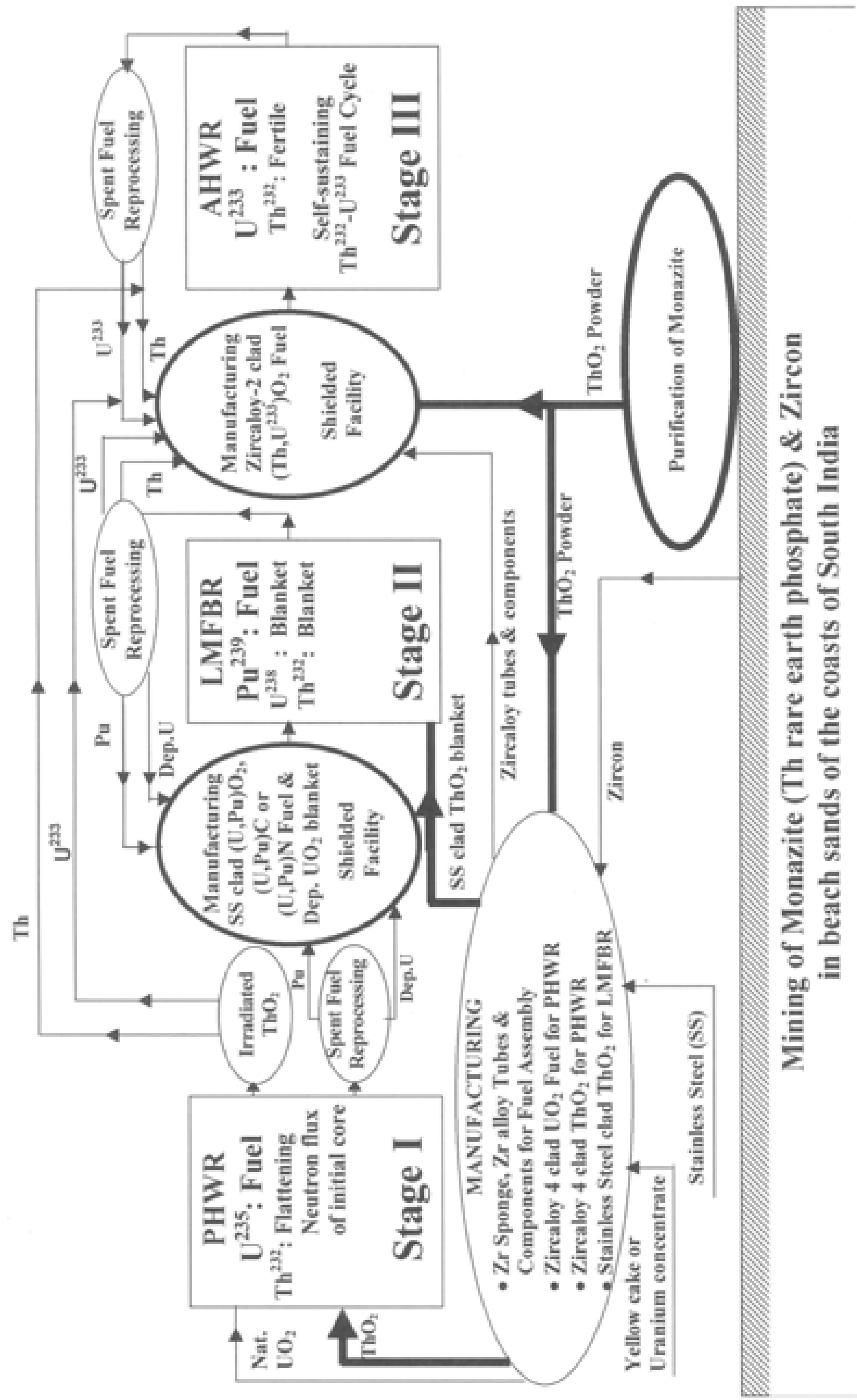

Figure A2.10 India's three-stage path to a closed, breeding thorium cycle (IAEA 2005).

A2-11. REFERENCES

Bae, K-M and M-H Kim, 2005, “Core Design for Heterogeneous Thorium Fuel Assemblies for PWR(I)-Nuclear Design and Fuel Economy,” *Nuclear Engineering and Technology*, 37, 1, pp. 91–100, February 2005.

Gambogi, J. “Thorium,” in *2011 USGS Minerals Yearbook*, United States Geological Survey, January 2013.

Galperin, A., Radkowsky, A. and M. Todosow, 1999, “A Competitive Thorium Fuel Cycle for Pressurized Water Reactors of Current Technology,” IAEA-TECDOC-1319, International Atomic Energy Agency, pp. 83–96, 1999.

Gillerman, V. S., 2008, “Geochronology of Iron Oxide-Copper-Thorium-REE Mineralization in Proterozoic Rocks at Lemhi Pass, Idaho, and a Comparison to Copper-Cobalt Ores, Blackbird Mining District, Idaho,” http://minerals.usgs.gov/mrerp/reports.html, 2008, Web page accessed August 4, 2009.

Hedrick, J. B., 1997, “Thorium,” *US Geological Survey, Mineral Commodity Summaries*, February 1997, pp. 176–177, 1997.

Hedrick, J. B., 2009, “Thorium,” *US Geological Survey, Mineral Commodity Summaries*, January 2009, pp. 170–171, 2009.

Hermes, W. H. and J. W. Terry, 2007, “Removing the Source Term – Thorium Nitrate Disposal at the Nevada Test Site,” *Proc. Health Physics Society 2007 Midyear Topical Meeting*, Knoxville, Tennessee, January 21–24, 2007.

Herring, J. S., et al, 2001, “ Low Cost, Proliferation Resistant, Uranium-Thorium Dioxide Fuels for Light Water Reactors,” *Nuclear Engineering and Design*, 203, pp. 65–85, 2001.

Herring, J. S., 2004, “Uranium and Thorium Resource Assessment,” *Encyclopedia of Energy*, ISBN 0-12-176480-X, Boston University, Boston, Massachusetts, 2004.

IAEA, 2005, “Thorium Fuel Cycle – Potential Benefits and Challenges,” International Atomic Energy Agency, IAEA-TECDOC-1450, May 2005.

Indian Rare Earths Limited (IREL), 2009, “Unit Profile,” http://www.irel.gov.in/scripts/unit.asp, Web page accessed August 3, 2009.

Kelly, T., et al., 2007, *Historical Statistics for Mineral and Material Commodities in the United States,* USGS Data Series 140, http://minerals.usgs.gov/ds/2005/140/, Web page accessed August 1, 2009.

OECD Nuclear Energy Agency, 2006, *Forty Years of Uranium Resources, Production and Demand in Perspective: the Redbook Retrospective*, OECD/NEA: Paris, 2006.

OECD Nuclear Energy Agency, 2008, *Uranium 2007: Resources, Production and Demand* (also known as *The Red Book*), OECD/NEA-IAEA, Paris 2008.

Oak Ridge Associated Universities (ORAU): Incandscent Gas Lantern Mantles, https://www.orau.org/ptp/collection/consumer%20products/mantle.htm; updated November 2009

Schapira, J. P. and R. K. Singhal, 1999, “Radiological Impact at the Extraction Stage of the Thorium Fuel Cycle,” Nuclear Technology, 129, 25-34, October 1999.

Unak, T., 2000, “What is the Potential Use of Thorium in Future Energy Production Technology?” *Progress in Nuclear Energy*, Vol. 37, 1-4, pp. 137–144, 2000.

U.S. Geological Survey, 1998, “Metal Prices in the United States through 1998,” pp. 155–157, 1998.

Kelly, T. D., and G. R., Matos, comps., 2008, *Historical Statistics for Mineral and Material Commodities in the United States*: U.S. Geological Survey, Data Series 140, http://pubs.usgs.gov/ds/2005/140/, Web page accessed August 1, 2009.

Van Gosen, B. S., V. S. Gillerman, and T. J. Armbrustmacher, 2009, "Thorium Deposits of the United States – Energy Resources for the Future?" U.S. Geological Survey, Circular 1336, 2009.

Wang, D., 2003, Optimization of a Seed and Blanket Thorium-Uranium Fuel Cycle for Pressurized Water Reactors," Ph.D. Dissertation, MIT, 2003, http://hdl.handle.net/1721.1/29956, Web page accessed August 1, 2009.

World Nuclear Association, 2009, Information Issue Brief 62, "Thorium," February 2009, www.world-nuclear.org/info/inf62.html, Web page accessed August 1, 2009.

World Nuclear News, 2009, "Thorium Use in CANDU Units to be Assessed," *World Nuclear News*, July 15, 2009.