MODULE A

Source Materials
(Uranium and Thorium)

Module A1

Uranium Mining and Milling

Module A1

Uranium Mining and Milling

This section provides comprehensive summaries of the long term uranium market in 2009 and 2012 that was reviewed again in 2016 with no changes recommended, and a less-detailed analysis of the near term (spot) market situation in 2009. It updates (2012) the long term cost forecasting methodology used in the 2009 report (2009 CBR) and adds a second, parallel forecasting methodology which basically supports the results of the 2009 analysis. To these forecasting methodologies, this update in 2017 adds a forecast based on time series analysis. It too supports the original forecast done in 2009. Since 2009 the Fukushima accident, the advent of very low natural gas prices, and other socioeconomic factors have greatly decreased the near term demand (next 20 years) for uranium. For this reason a depressed spot market now (2017) exists and will be discussed in new reports referenced below. The authors believe that despite near-term depressed market conditions, there will continue to be a long term (rest of century) demand for uranium supporting a viable long term pricing structure.

A1-MD. SHORT DESCRIPTION OF METHODOLOGY USED FOR ESTABLISHMENT OF MOST RECENT COST BASIS AND UNDERLYING RATIONALE

- **Constant $ base year for 2017 Update:** FY 2017
- **Nature of this 2017 Module update from previous AFC-CBRs:** Escalation and a new section presenting time series analysis of uranium prices. Section A1-6.2 discusses historic uranium prices and then a price forecast for uranium prices based on historic data.
- **Estimating Methodology for latest (2009 AFC-CBR) technical update from which this 2017 update was escalated:** Analysis (in 2009) of long term historical trends and their forward projections for uranium and other specialty metal commodities. In 2012 and 2017 additional trend analyses were added, which basically supported the 2009 cost ranges. Escalation of 14% from 2009 to 2017 is utilized to establish the 2017 cost ranges. The escalation factor of 1.14 is calculated from the recently updated Table in the "Escalation Considerations" chapter of this report.

A1-RH. REVISION HISTORY

- **Version of AFC-CBR in which this Module first appeared:** 2004 as Module A (Uranium Mining and Milling). In 2009 AFC-CBR Module A was renamed "Source Materials" and separated into Module A1 for Uranium Mining and Milling and Module A2 (Thorium Mining and Milling).
- **Latest version of module in which new technical data was used to establish unit cost ranges:** 2009 with additional technical analysis in 2012 and 2017 to support 2009 methodology and unit cost values.
- **New technical/cost data which has recently become available and will benefit next revision:** In this revision time series analysis of uranium spot market prices has been added. Although from a different methodological approach, this analysis supports the forecast estimates first documented in 2009.
- **Other cost-related technical areas which may benefit from further literature research**: Improvements to in-situ mining technology due to advancements in hydrocarbon fracking, possible recovery of uranium from used fracking liquids, continued research and improvements in recovery of uranium from seawater.

- **A market analysis in 2016 served as a "spot check" on the situation in the market for uranium**. A summary of that spot check is included in the text below in Section A1-6.6.

A1-1. BASIC INFORMATION

The authors recognize that uranium and enrichment spot prices have recently moved outside the range provided in this cost basis. Prices have declined from peak, "Nuclear Renaissance" values seen in 2007, and are now strongly suppressed. Price trends continue to be evaluated and the cost ranges in the report may continue to be revised as appropriate in future updates. **The cost basis reflects reasonable expectations about uranium and enrichment long-term contract prices applicable to reactors with long operating lives, rather than reflecting market spikes as experienced in the 1970s and observed in the spot market U_3O_8 prices circa 2007.**

This module covers the factors involving extraction of uranium from the earth through production of uranium concentrate in the form of U_3O_8, commonly known as "yellow cake." Supply of uranium for use in the commercial nuclear industry in the United States is obtained from both domestic and foreign supplies. Uranium is somewhat unique among fuel resources in that nontraditional or secondary supply currently provides a significant portion of uranium requirements. The sources of uranium for any given year's demand are classified as originating from primary supplies representing newly extracted and processed uranium from the earth's surface or from secondary supplies such as existing inventories of natural or low-enriched uranium (LEU), highly enriched uranium (HEU), mixed oxide fuel (MOX), reprocessed uranium (RepU), and reenrichment of depleted uranium (tails). In general, the difference between the total demand for uranium to produce new fuel and that supplied by secondary sources results in the market demand for newly extracted uranium from mining of the earth's surface.

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 uranium available for use. These indications are expressed in an estimated cost to reclaim and utilize the reserves with reasonably established methods. Adequacy of the market to supply uranium and appropriateness of pricing are influenced by many factors including overall demand, secondary supplies, primary supplies, lead time for discovery and production, cost of extraction, and such factors as captured markets. Extensive analyses of such factors are performed regularly and published in a biennial report by OECD/NEA-IAEA known as the *Red Book* (OECD 2006a) and annually by DOE-EIA in the *Uranium Industry Annual* (DOE EIA 2008). IAEA has published an *Analysis of Uranium Supply to 2050* (IAEA 2001) evaluating uranium supply to three distinct uranium demand cases. These ranged from a "Low" uranium demand case, reflecting a low energy demand growth and a phase out of nuclear power by 2100, to a "High" demand case, reflecting high economic growth with significant development of nuclear power. A "Middle" demand case, which was also defined, is mainly driven by sustained development of nuclear power worldwide, including the demand in developing countries. Such analysis permits the estimated reserves to be evaluated relative to adequacy of supply, expectations of relative pricing, and projections of ability to make the resources available for utilization in a timely manner.

Two unit systems for quantifying uranium masses are in widespread use in literature. These are pounds of U_3O_8 (lb U_3O_8) and kilograms of U (kg U), where 1 kg U = 2.60 lb U_3O_8. In the figures and tables accompanying this module, the units used by individual source documents are generally preserved.

A1-2. FUNCTIONAL AND OPERATIONAL DESCRIPTION

A1-2.1 Mining and Milling

Uranium is widely distributed throughout the crust of the earth. The ability to extract the uranium in a practical and cost-effective manner depends on the relative grade of the ore to be mined (i.e., the percentage of uranium in the ore body), the type of formation in which it resides, and the location. Uranium, on average, is more prevalent in the earth's crust than such economically important metals as silver and tungsten (Table A-1); it is a constituent of most rocks and even of the sea. Table A-2 shows some typical concentrations in ppm (parts per million).

Table A1-1. Crustal abundance (grams/tonne) of selected elements. (1 tonne = 1 metricton = 10^3 kg = 10^6 grams)

Element	Grams/tonne
Gold	0.004
Silver	0.07
Tungsten	1.5
Molybdenum	1.5
Uranium	2.8
Thorium	7
Lead	13
Copper	55
Zinc	70
Iron	50,000

Table A1-2. Typical concentrations (uranium parts per million).

Substance	Uranium Concentration (ppm)
High-grade ore—2% U	20,000
Low-grade ore—0.1% U	1,000
Granite	4
Sedimentary rock	2
Earth's continental crust (av)	2.8
Seawater	0.003

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. At present, neither the oceans nor any granites are ore bodies, but conceivably either could become so if prices were to rise sufficiently (UIC 2005).

The cost of meeting environmental requirements is also a major factor in the attractiveness of the ore body. Although there are varied means of extracting the uranium to "yellow cake," only two basic approaches will be discussed here, conventional mining (surface pit or deep) and in situ leaching, as depicted in Figure A1– 1. The quantity of ore required to produce a tonne of uranium will depend on the average grade of the ore. Typically amounts from 10–1000 tonnes of ore are processed to produce a single tonne of uranium (e.g., ore grade 10% to 0.1% U); although, in certain circumstances lower-grade ore bodies are being tapped. The Olympic Dam mine in Southern Australia, for instance, holds the largest-currently known ore body in the world—greater than 1 million tonnes of yellow cake. The average grade of Olympic Dam ore is only 0.04% U, but the ore is rich in copper (1.1%) and gold (Global InfoMine, Inc. 2005). The presence of iron, copper, and gold in this and other breccia complex deposits allow profitable U mining at lower market prices than would otherwise be the case.

Mining techniques, as depicted below, will thus be impacted by the difficulty in reaching the ore, the grade, and the amount of secondary waste to be generated.

A1-2.2 In situ Leaching

With the in situ leaching technology (Figure A1– 2), a leaching liquid (e.g., ammonium-carbonate or sulfuric acid) is pumped through drill-holes into underground uranium deposits. The solution dissolves and mobilizes the deposit, and the uranium bearing liquid is pumped out from below. The solution is further processed through a series of ion exchange resins or solvent extraction processes and eventually precipitated, dewatered, and yellow cake is produced. The yellow cake is packaged in 55-gallon steel drums for shipment to the conversion plant. The process recovers the leachate, which is adjusted and recycled back into the injection wells. Very little secondary waste is formed. This technology can only be used for uranium deposits located in an aquifer in permeable rock, confined between nonpermeable rocks.

The advantages of in situ leaching are (a) elimination of stockpiling and hauling of ore; (b) elimination of the crushing, grinding, and other milling operation; (c) elimination of large-scale excavations; (d) reduction of risks to miners because they do not have to work underground; and (e) a very small portion of the radioactivity (~5%) of the ore reaches the surface. Disadvantages include (a) risk of leaching liquid excursions beyond the uranium deposit and subsequent contamination of ground water, (b) production of some amounts of waste sludge and waste water when recovering the leaching liquid, (c) impossibility of restoring natural conditions in the leaching zone after finishing the leaching operation, and (d) a low recovery rate of approximately 50% is considered optimum (Diehl and Schwedenteich 2005; Cochran and Tsoulfanidis 1999).

A1-2.3 Open Pit and Underground Mining

Historically most uranium ore has been mined in open pit or underground mines. The uranium content of the ore is often between only 0.1% and 0.2%. Therefore, large amounts of ore have to be mined to acquire uranium. Waste rock is produced during open pit mining when overburden is removed and during underground mining when driving tunnels through non-ore zones. Piles of so-called waste rock often contain elevated concentrations of radioisotopes compared to normal rock. They are typically returned to the pit and covered with overburden. Other waste piles consist of ore with too low of a grade for processing. The transition between waste rock and ore depends on technical and economic feasibility.

The uranium bearing ore must be stockpiled and subsequently hauled to the uranium mill (Figure A1–3) where it is processed and concentrated into yellow cake. A uranium mill is a chemical plant designed to extract uranium from ore. It is usually located near the mines to limit transportation. The ore has to be crushed and ground into a fine powder and then roasted to remove most of the organic matter. In most cases, sulfuric acid is used as the leaching agent, but alkaline leaching is also used. As the leaching agent not only extracts uranium from the ore, but also several other constituents like molybdenum, vanadium, selenium, iron, lead, and arsenic, the uranium must be separated out of the leaching solution. This procedure may be an ion exchange or solvent extraction type of process. The uranium is eventually precipitated out and washed, centrifuged, and dried; and the yellow cake is placed in 55-gallon steel drums for shipment to the conversion plant. In some cases, uranium has been removed from low-grade ore by heap leaching. This may be done if the uranium content is too low for the ore to be economically processed in a uranium mill. The leaching liquid (often sulfuric acid) is introduced on the top of the pile and percolates down until it reaches a liner below the pile, where it is caught and pumped to a processing plant.

Waste from the uranium mill is released to a tailings pond where it forms sludge. The tailing ponds receive nearly all the radium and other decay products of the original ore. The amount of sludge produced is nearly the same as that of the ore milled. At a grade of 0.1% uranium, 99.9% of the material is left over. Apart from the portion of the uranium removed, the sludge contains all the constituents of the ore including heavy metals and other contaminants, such as arsenic, as well as chemical reagents used during the milling process. As a result, such tailings require control to safeguard the surrounding environment from radioactive contamination or unwanted radiation exposure. Control of the tailings falls under the Uranium Mill Tailings Radiation Control Act and U.S. Environmental Protection Agency standards.

Advantages of open pit or deep mining are usually centered on a higher recovery of the uranium ore, or, in the case of underground mining, very little surface disturbance. Obvious disadvantages include the large amount of secondary waste that is generated—the 60 million tonne Olympic Dam tailings pile, for example, presently covers over 500 hectares—as well as a much larger exposure of operating personnel to radiation and potential contamination. Deep mining has the added risk of cave-ins, subsidence, and hazards of radon gas generation during mining operations.

A1-3. PICTURES AND DIAGRAMS

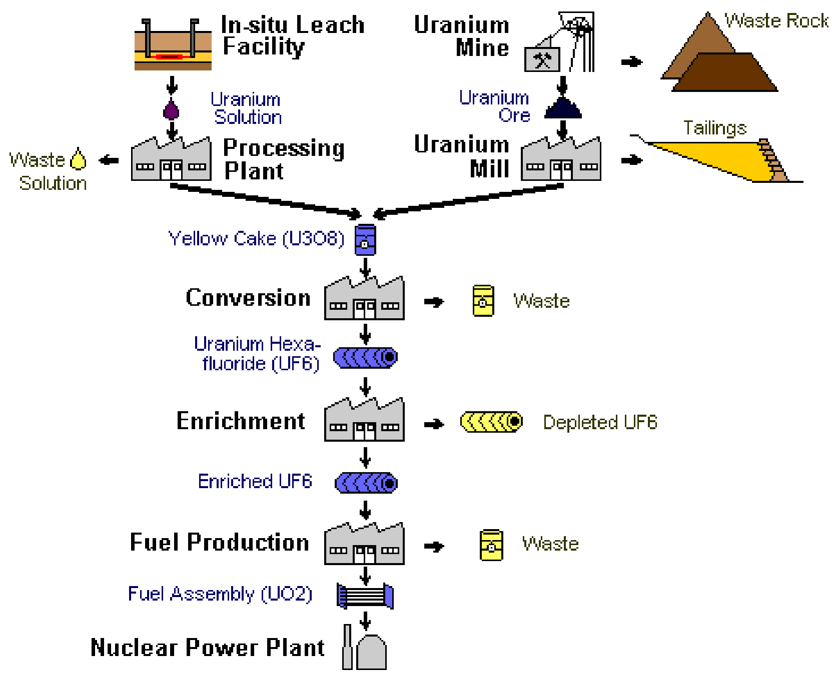


Figure A1– 1 Nuclear fuel production chain for light water reactors (Diehl and Schwedenteich 2005).

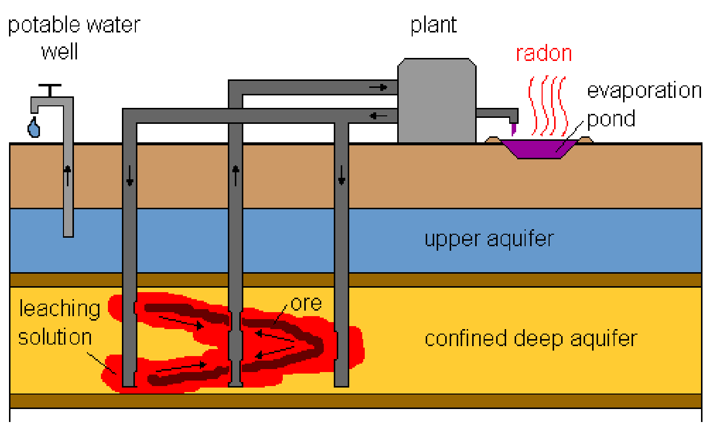


Figure A1– 2 Typical in situ leaching operation (Diehl and Schwedenteich 2005).

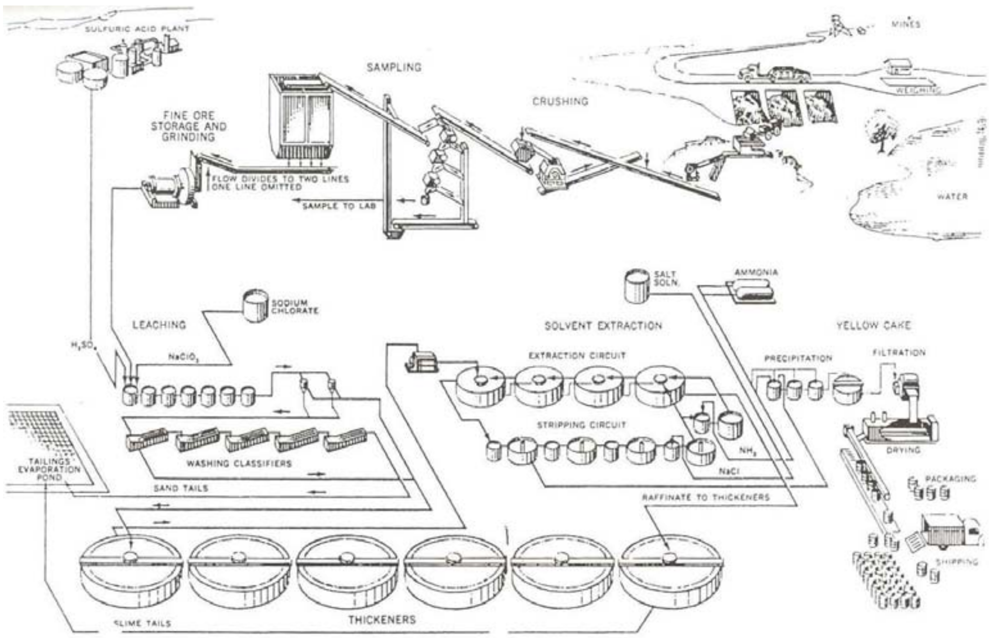


Figure A1– 3 Typical uranium mill (EPA 1995).

A1-4. MODULE INTERFACES

The product of Module A 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. The requirements for Module D1 can be made up from uranium originating from mining with subsequent conversion and enrichment, or from a number of secondary sources including but not limited to inventory reduction, HEU blend down to LEU and RepU. Module A should, therefore, be directly linked to Modules B and C with the potential for planned inventory buildup by the suppliers.

A1-5. 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.

A1-6. COST BASES, ASSUMPTIONS, AND DATA SOURCES

The cost basis for uranium 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 is also impacted by secondary sources of uranium already existing in many forms in the overall fuel cycle. The following discussions highlight the key factors relative to the actual supply and demand for newly produced uranium.

The 2009 CBR presented a uranium price forecast that represents expected trends over many decades. The basis for that forecast was USGS historical world production and price data series for 35 mineral commodities (USGS 2005). Data for many of these minerals extends back to 1900, so that more than one hundred years of historical prices and production are given in most of the series. Uranium is unexceptional by several measures used to characterize mineral commodities: its crustal abundance, average grade of ore being recovered and known reserves all fall near the middle of the 35 commodities in the data set.

Therefore, the 2009 CBR postulated that uranium price trends over the coming 100 years are well represented by the range of historical trends for the surrogate commodities. The data used for the 2009 CBR forecast extended to 2004; USGS has subsequently updated the data series through 2010. Most commodities have exhibited a long term trend of gradually declining price overlain by more dramatic increases and decreases associated with the boom-bust cycles typical of mineral prices. Since many commodities experienced price booms during the late 2000s, the extension to 2010 is significant in that it incorporates part of another boom cycle. Please see the 2009 CBR for detailed documentation of the model and justification for using the 35 commodities as surrogates for uranium.

The mineral price history approach will provide one input to the long term price range forecast in this update. A second input, not utilized in the 2009 CBR, will be the uranium price elasticity model developed by MIT for its 2011 study (MIT 2011) on the future of the nuclear fuel cycle. The two sets of results will be averaged to develop the module forecasts, representing equal weighting of the approaches.

Mineral Commodity Index

Table A1– 1 compares the USGS data set for this update to that used in the 2009 CBR. The USGS adjusted the price data in its set to constant year 1998 dollars, so all data and conclusions presented here are based upon inflation-adjusted price trends. During the 2004-2010 period for which new data is available, most prices and annual production rates rose. As discussed in the 2009 CBR, short term price escalation is driven in part by rapidly increasing demand, especially if the increase is larger than anticipated. In the longer term, conflicting forces act to shape production cost and price trends. Depletion of the most economically attractive deposits shifts production to costlier (e.g. lower grade, deeper, more difficult to mill) resources. But the progress of technology leads over time to reduction of recovery costs from known deposits as well as to new methods for prospecting and exploiting previously unknown or unattractive sources.

Table A1– 1 Comparison of 2009 CBR and 2012 CBR mineral commodity data sets.

Mineral commodities in survey	33 (35 in 2009 CBR)
Timespan of data	1900-2010 (1900-2004 in 2009 CBR)
Commodities whose price has increased from 2004 to 2010	24 of 33
Commodities whose annual production rate has increased from 2004 to 2010	26 of 33
Largest relative price increase, 2004-10	Cadmium, \$1040 -> \$2820/tonne1
Largest relative price drop, 2004-10	Arsenic, \$804 -> \$325/tonne1
1. Given in 1998 dollars as in the data source.	

The simple model presented in the 2009 CBR and summarized here aims to capture the long term price trend that results from the interplay of these upward and downward acting forces. It fits each price history to a function

$$P = Ce^{Mt} \tag{1}$$

where

P [\$/tonne] = commodity price (given in constant year 1998 dollars in [2]),

t [-]= year of data – first year for which data is available,

C [\$/tonne] and *M* [-] = regression coefficients.

If the fitting coefficient *M* is positive, the mineral has shown a generally rising price trend over the data period. If *M* is negative, the price has been declining. Table A1– 2 shows the *M*-coefficients for the data sets used in the 2009 and 2012 CBRs.

Table A1– 2 M-coefficients for mineral commodities in the 2009 and 2012 data sets.

	2009 CBR Data Set	2012 CBR Data Set		2009 CBR Data Set	2012 CBR Data Set
Coverage Period	1900-2004	1900-2010	Coverage Period	1900-2004	1900-2010
Aluminum	-2.04E-02	-1.93E-02	Lead	-5.22E-03	-4.04E-03
Antimony	1.36E-03	1.59E-03	Lithium	-2.54E-02	-2.44E-02
Arsenic	-8.70E-03	-1.06E-02	Magnesium	-2.32E-02	-5.01E-03
Bauxite	-7.41E-03	-8.51E-03	Manganese	3.34E-03	4.69E-03
Beryllium	-1.86E-02	-2.09E-02	Mercury	-1.24E-02	-1.16E-02
Bismuth	-2.10E-02	-2.18E-02	Molybdenum	-7.48E-03	-2.49E-03
Boron	-1.53E-03	-1.91E-03	Nickel	-4.35E-03	-2.19E-03
Bromine	-2.83E-02	-2.83E-02	Platinum	-4.63E-03	-3.91E-03
Cadmium	-2.43E-02	-2.45E-02	Pumice	-1.39E-02	5.60E-04
Chromium	7.74E-03	9.13E-03	Rhenium	-4.99E-02	-2.29E-02
Cobalt	-4.87E-03	-4.20E-03	Silver	-1.28E-03	-3.88E-05
Copper	-6.38E-03	-4.49E-03	Tantalum	-5.87E-03	-1.07E-02
Germanium	-2.12E-02	-1.06E-02	Thorium	-4.64E-03	[1]
Gypsum	4.06E-03	-3.27E-02	Tin	1.28E-03	1.48E-04
Indium	-4.07E-02	-6.57E-03	Titanium	-3.95E-02	[1]
Iodine	-1.53E-02	6.45E-03	Tungsten	-1.95E-03	-3.43E-03
Iron Ore	2.88E-03	3.85E-03	Vanadium	-1.21E-02	-1.67E-02
			Zinc	-3.78E-03	-2.91E-03

1. Data for 2005-10 for thorium and titanium were not available, so these commodities were not used in the updated data set. If they were omitted from the set used in the 2009 CBR, the effect would be minimal: the mean would change from -0.0118 to -0.0112 and standard deviation from 0.0136 to 0.0130.

Seven of the 33 *M*-coefficients in the updated data set are positive, against six in the set that did not include the 2005-10 data. The *M*-coefficients are once again close to normally distributed (Figure A1– 4). Fitting them to a normal distribution yields the mean and standard deviation shown in Table A1– 3.

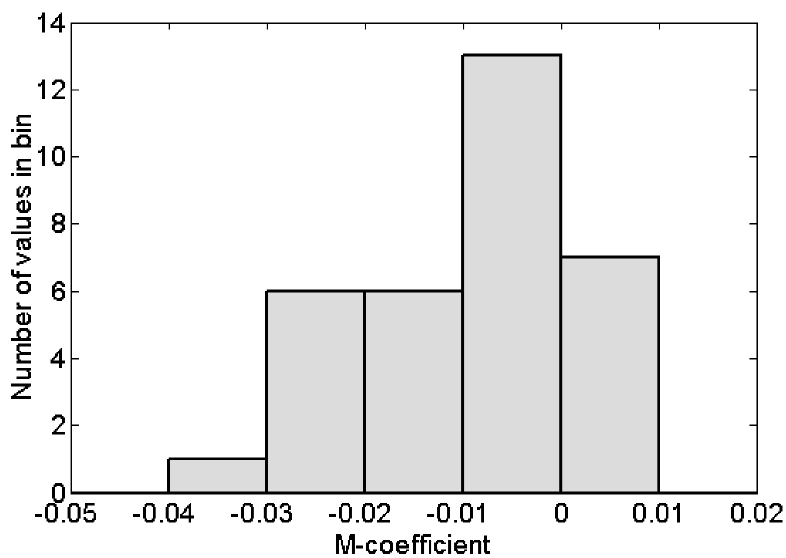


Figure A1– 4 Distribution of M-coefficients.

Table A1– 3 Mean and standard deviation of M-coefficient values for the 2009 and 2012 data sets.

	2009 CBR Data Set	2012 CBR Data Set
Data coverage period	1900-2004	1900-2010
Mean	-1.18E-02	-8.43E-03
Standard Deviation	1.36E-02	1.07E-02
Mean + 2 S.D.	1.53E-02	1.30E-02
Mean - 2 S.D.	-3.90E-02	-2.99E-02

The nominal uranium price forecast is developed by considering the mean value of the M-coefficient. To represent a 95% confidence interval, the high and low forecasts utilize the mean plus and minus two standard deviations, respectively. Forecasts are developed by projecting the uranium price forward in time using Equation (1). To do so, a value for the price at the start of the forecast, C, is needed. C should represent a reasonable estimate of the marginal production cost of the commodity, i.e. the price if the market were in equilibrium. The 2009 CBR took C to be \$120/kg U, and indeed uranium prices have remained near this level between 2009 and 2012 (Figure A1– 3). Therefore, C will continue to be chosen as \$120/kg U for this update and the reference date against which the time, t, is measured in Equation (1) will remain 2010.

Using Equation (1) with C = \$120/kg U and the M-coefficients of Table A1– 3 results in the price trends shown in Figure A1– 5. To develop single-valued estimates for the CBR, numerical averages of each of the curves over the 100 year time period starting in 2010 were taken. The mean forecast is seen to have increased slightly with the 2012 CBR data set, reflecting the effect of including the 2005-10 price boom in the data series from which the *M*-coefficients were derived. On the other hand, the 95% confidence interval has narrowed somewhat[a].

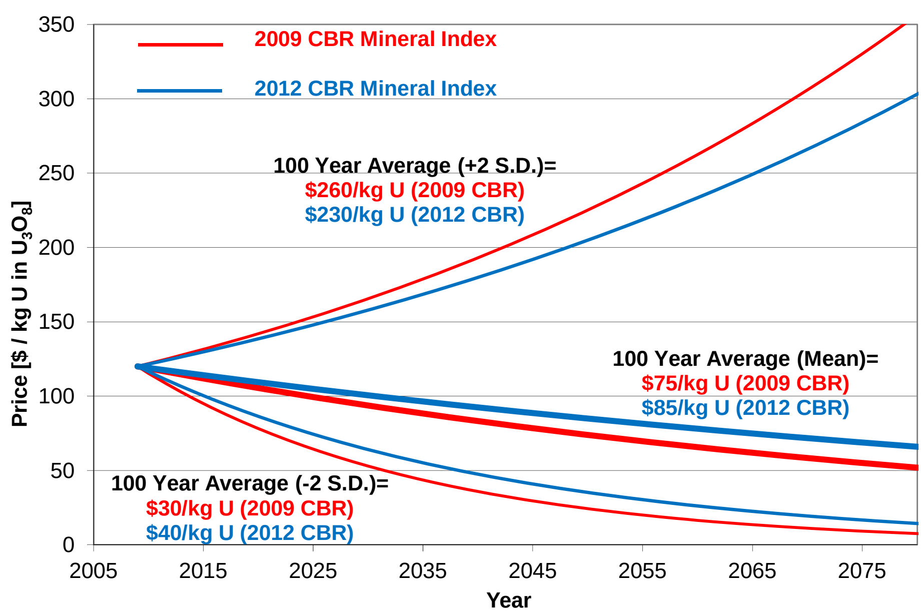


Figure A1– 5 Mean (heavy lines) and +/- 2 standard deviation (thin lines) projections from the 2009 and 2012 CBR Mineral Index models.

[a]. Once the data set was extended through 2010, the M-coefficients were found to have become more tightly grouped. Some commodities with very negative coefficients in the data set to 2005 saw substantial price increases from 2005-10 and their M-coefficients drew closer to the mean (e.g. indium, M=-0.0407 through 2005, M=-0.00657 through 2010).

A1-6.1 MIT Price Elasticity Model

Few quantitative estimates exist for uranium price trends over time frames of half a century or longer. The 2009 CBR reviewed several of these and dismissed them for considering only the resource depletion effects that tend to push prices higher over time while neglecting technological change and other factors that have held commodity prices down over the decades. The 2011 MIT report “The Future of Nuclear Power” (MIT 2011) includes a forecast that aims to account for forces that act to push prices both upward and downward over time.

The form of the MIT forecast is as follows:

$$\left(\frac{P}{P_0}\right)=\left(\frac{U}{U_0}\right)^{\theta} \qquad (3)$$

where

U [tonnes U] = cumulative uranium extracted,

U_0 [tonnes U] = cumulative uranium extracted up to an initial reference time,

P [$/kg U] = uranium price when cumulative uranium extracted reaches U,

P_0 [$/kg U] = uranium price at an initial reference time,

θ [-] = exponent that depends on economies of scale, learning rate and resource vs. grade elasticity.

For consistency with the mineral index model, the initial reference time is chosen as 2010 with initial price P0 = $120/kg U and cumulative uranium production up to that date U0 = 2.0x106 tonnes U. This model predicts the price as a function of the total cumulative amount of uranium extracted, U, at some future date. Therefore, it depends on the rate at which uranium is produced into the future. Since the CBR presently does not couple costs or prices to production capacity or cumulative production, an assumption regarding future uranium production, which stood at nearly 55,000 tonnes U/year in 2010 and 2011 [4], is needed. This will be that uranium production increases at 2.6%/year, corresponding to the mid-range nuclear power growth rate estimated by the World Nuclear Association for 2011-30 (WNA 2012).

The θ coefficient is analogous to the M-coefficient in the mineral index model in that it determines whether the price will trend higher or lower. MIT used a range of published estimates of the amount vs. concentration of uranium in the ground, the rate at which technological change acts to reduce production costs in related industries, and the general effects of scale economies to forecast a distribution of values for θ. See Ref. (MIT 2011) for details. Following the approach taken for the mineral index, upper and lower bounding scenarios on θ were chosen to correspond to a 95% confidence interval[b] (Table A1– 4).

Table A1– 4 Mean and bounding theta-coefficients for the MIT price elasticity model.

Mean	1.10E-01
Upper Confidence Interval Bound	4.40E-01
Lower Confidence Interval Bound	-2.50E-01

Figure A1– 6 shows MIT elasticity model projections and compares them to the 2012 CBR mineral index curves previously shown in Figure A1– 5. The projections are largely in agreement, though the MIT model shows the expected price (heavy green line) trending somewhat upward while the mineral index

[b]. Ref. [3] only gave a graphical representation of the □ distribution, so the confidence intervals were estimated from the plot.

model forecasts a decreasing price (heavy blue line). The 95% confidence interval associated with the MIT model is also seen to be narrower than that of the mineral index approach[c].

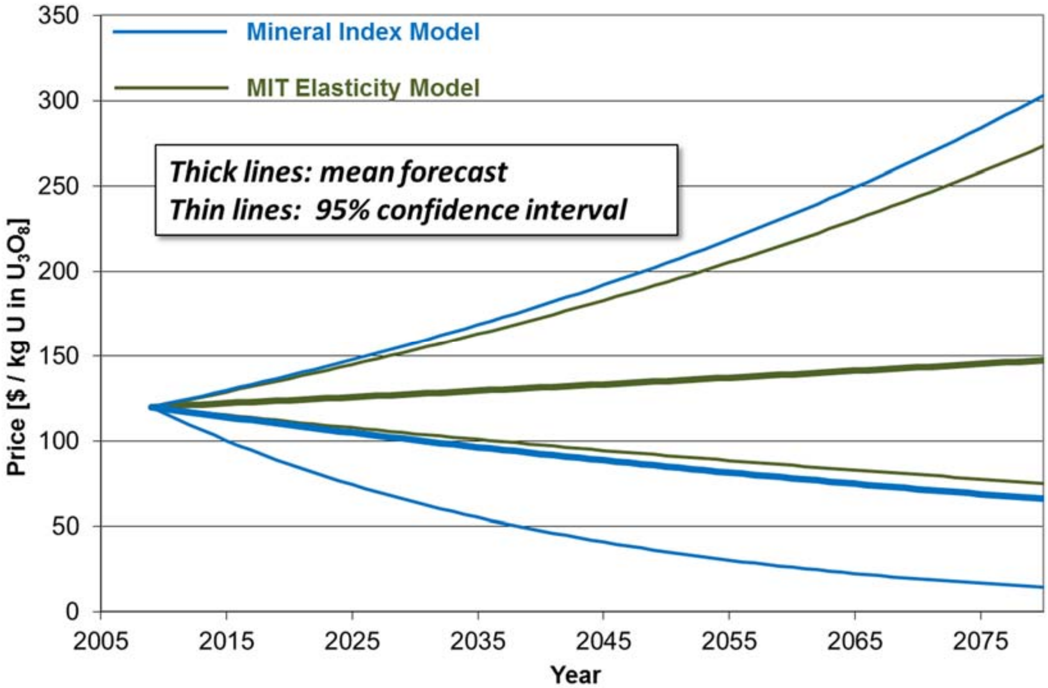


Figure A1– 6 Mean (heavy lines) and 95% confidence interval (thin lines) projections from the MIT Elasticity and Mineral Index models.

A1-6.2 Time Series Analysis of Uranium Spot Market Prices

Analysis of causal relationships is one approach to forecast uranium prices; time series analysis is an alternative. Whereas causal analysis measures the statistical relationship among a set of variables, analysis of time series data measures the statistical relationship of observations on the same variable in the historic record. The historic relationship can then be used to generate forecasts of the variable. This section presents a time series analysis of uranium prices. Coupled with the causal analysis in the previous section, the two methods provide a more robust base of what to expect for uranium prices.

The data for this analysis are from two locations. Roskill (1991) presents uranium price data, (USD/lb) from the US Atomic Energy Commission (USAEC) and from the Nuclear Exchange Corporation (NUEXCO). The International Monetary Fund (IMF) (IMF 2017) publishes commodity prices from NUEXCO, also in USD/lb. Data from USAEC covers the time from 1948 – 1971 and NUEXCO data covers 1972 – 2016. The data, converted to USD/kg, are shown in Figure A1– 7 . Current values are made constant using the escalation method described in Chapter 7 of the Cost Basis Report.

[c]. The confidence interval on the MIT model would be wider if differences in the U demand growth rate were incorporated. A high demand growth rate would lead to more rapidly changing prices. This and other cost feedbacks from plant or industry capacity and throughput may be included in a future update to the Cost Basis Report.

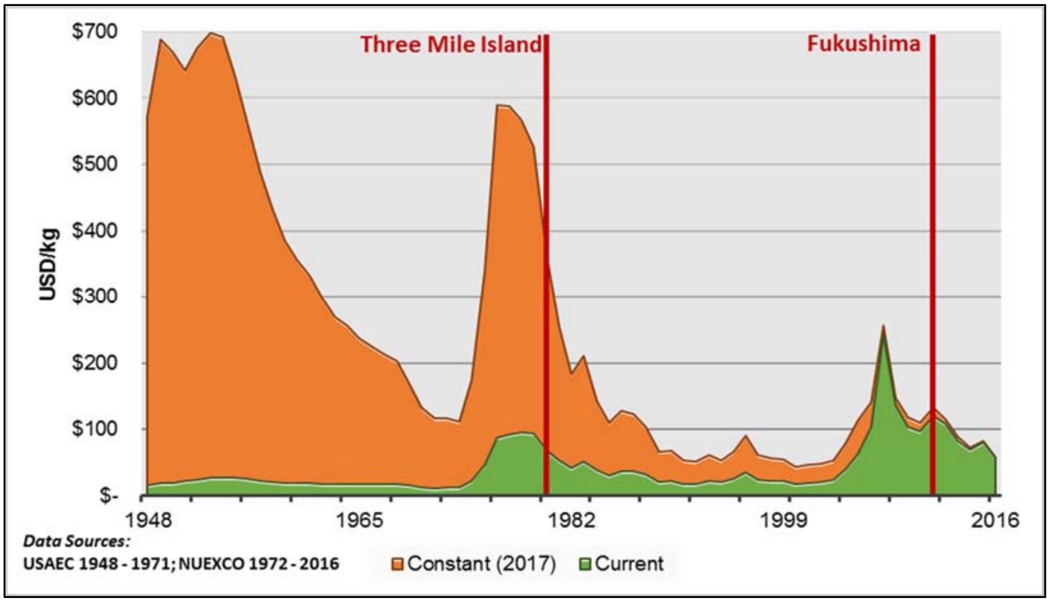


Figure A1– 7 Uranium prices in constant and current dollars annually.

In the analysis that follows, uranium prices in constant 2017 USD (the orange data series in Figure A1– 7) are used as the underlying data source. The timeframe of the data, however, becomes a choice the analyst must make. The analyst could use the entire data series, beginning in 1948, to forecast future uranium prices. Or a subset of the data could be used. The choice depends on at least two important pieces of information: the analyst's expectation of the similarities in the historic record to what one might reasonably expect in the future, and statistical testing to compare prediction error. Visualizing the data from the beginning of the nuclear industry (1948) up to the point of Three Mile Island (TMI) suggests a long period of declining prices with a significant spike just preceding TMI. Following TMI uranium prices entered a long period of declining prices up through the early 2000s, at which point uranium prices, and all energy prices for that matter, spiked. Following the price spike of 2008 uranium prices again entered a period of decline. So which period in the data best represents what one might reasonably expect to approximate market conditions for uranium going forward?

For the uranium price forecast presented here the early days of nuclear, i.e. the period prior to TMI, are not used. The large starting point for price in 1948 is not likely representative of prices one should expect in a well-established market like the uranium market today. One might wonder at the extent that Fukushima had on uranium prices, but interestingly the figure suggests that uranium prices were in a downward trend at the time Fukushima occurred. Based on this intuition, the period of data used in constant 2017 prices, in the forecast analysis below is 1980 – 2016, but coupled with statistical testing. The discussion will return to this decision later.

The central idea in time series analysis is that there is some process that fits a data series, and that process can be used to forecast expectations of what might occur going forward. A simple time trend is a form of this analysis, an algorithm computes the mean values across time and from it generates a trend of possibilities. The simple trend can become more sophisticated with alternative forms such as the moving average (MA) where the average is computed across discrete time periods. For example an MA(2) process is one where the moving average is computed based on the average moving across two periods at a time. Beyond time trend analysis, time series processes can be fit to a stochastic processes. That is the stochastic process measures the randomness observed in the data series then projects a forecast based on the observed randomness in the historic record. Statistical tests are then employed to measure the 'goodness of fit' of each process. Trend-based processes can be compared to stochastic processes based on how well the process or trend fit the data. Examples of stochastic processes include Brownian motion, autoregressive processes, or generalized autoregressive conditional heteroscedasticity. Once the alternative processes have been fit to the data, the AIC test (Akaike Information Criterion) is used to measure goodness of fit.

Data stationarity is an important statistical property in fitting a stochastic process to time series data. Because the stochastic process fits the randomness of the data, if an underlying trend exists it must first be removed. If not first removed, then the computed mean and variance of the data misrepresent the randomness in the data. The autocorrelation function (ACF) and the partial autocorrelation function (PACF) measure the extent of stationarity in the data. The ACF and PACF are plotted in the correlograms shown in Figure A1– 8 for uranium prices over 1980 – 2016.

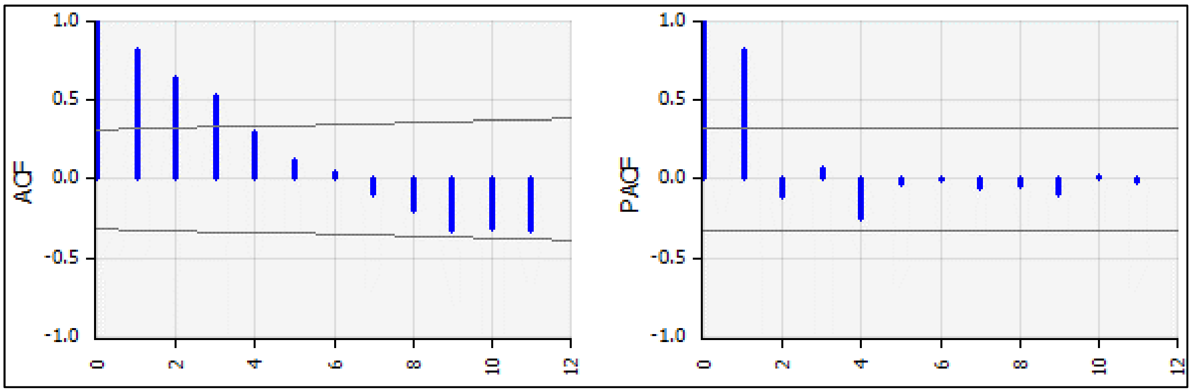


Figure A1– 8 Autocorrelation and partial correlation plots of uranium price data, 1980 – 2016.

The correlogram is a tool to visualize the statistical relationship between a data observation at any point in time and the lagged observation of the same variable. In it the vertical axis measures the correlation, where 0 indicates no correlation and 1 indicates perfect correlation, and the horizontal axis measure the number of lagged periods. The ACF plot illustrates that for a lag period of 1, i.e. 1 year, the data are almost correlated as indicated by a correlation factor of approximately 0.75. That is, the uranium price in year *t* is almost perfectly correlated with the uranium price in period *t* – 1. Further, the ACF indicates that almost 6 lags are required (i.e. 6 years) before the correlation across time periods dissipates. The PACF controls for correlation across lags. Whereas the ACF measures the correlation between periods, it does not control for the fact that correlation has already been measured. In the example given above, the data are correlated for up to 6 periods. That is given a signal impact in year *t* – 6, the ACF does not capture the correlation from the signal across periods up to year *t*. In contrast, the PACF accounts for the correlation across periods so that if the signal occurs in year *t* – 6 the PACF measures the correlation between *t* – 6 and *t* directly and accounts for the correlation in the years between. Looking at the PACF function, uranium prices are strongly correlated for 1 period. Taken together, the ACF informs that uranium prices reflect price signals that happen in a given year for up to 6 years, but he PACF tells us that the largest impact of signal remains for only a single year. One can interpret this as uranium prices are strongly correlated with a one-year lag but noise in the data takes about 6 years to dissipate out. These two correlograms inform that the data series is sufficiently stationary to use in forecasting.

Figure A1– 9 shows the uranium forecast model plotted against the historical data. The historical path indicates the data series from 1980 through 2016. One can think of the figure as representing a forecast in 1980 and asking the question, "How good of job will the forecast model do at predicting uranium prices?" Before discussing the implications of the figure in greater depth, it is first necessary to discuss how it was produced and the data used to generate the forecast.

Noted earlier, Figure A1– 7 shows that in the data series of uranium prices there are at least two distinct time periods and arguably three. First, the time period that could be used for forecasting analysis is from 1948 to 2016. This is analogous to the logic that uranium prices from the beginning of the nuclear age up through the present ought to be used to generate the forecast of possible uranium prices. A second school of thought is that the nuclear industry was fundamentally different after the event of TMI. This is in part due to the nature of regulation change that followed TMI, but also the fact that many of the early difficulties in getting the nuclear industry underway were resolved by about this time. The third possibility for the seed data for a uranium forecast is TMI up to just prior to Fukushima. This logic suggests that Fukushima is an anomaly and is not representative of what the nuclear industry might look like going forward. So which of these time series of data should be used to forecast uranium prices? Figure A1– 9 is based on uranium prices from 1980 to 2016, and the next paragraph discusses why.

The software used for this is analysis is called @Risk (Palisade 2016). The time series module of @Risk allows the analyst to load seed data and then an algorithm in the software compares the seed data to a number of different stochastic, time series processes. The software presents the analyst with several possible choices and computes the AIC statistics for each model fit. The AIC measures the goodness of fit of the data with the stochastic process, and it is used as a statistic of relative comparison. In the analysis, each possible time frame for data are entered into the software (i.e. 1948 – 2016, 1980 – 2016, and 1980 – 2010). The analyst uses @Risk to fit stochastic processes to each time frame then compares the fitted models for each data series. Using the AIC statistic, a model is selected to represent each of the possible choices for seed data. With the three fitted models arrives the question, "which model best predicts the historic data?"

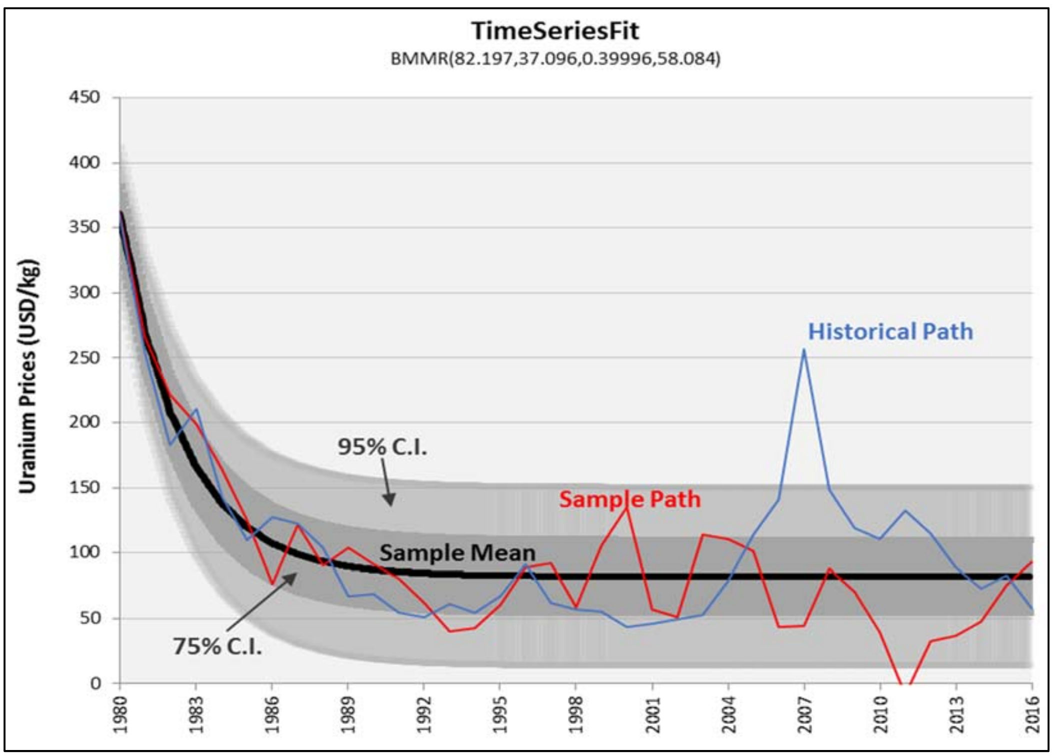


Figure A1– 9 Comparing predictions using time series fitted model with historical data.

To answer this question each model is used to predict observations over the same time frame as the seed data. This allows the analyst to compare how well each model predicts history. The statistic used to compare these predictions is called the Mean Absolute Percentage Error (MAPE). The equation for MAPE is given as where t indicates the year of observation:

$$\text{MAPE}_t = \frac{|\text{Observation}_t - \text{Prediction}_t|}{\text{Observation}_t} * 100 .$$

For each fitted model the MAPE is computed in each time period. Then, because the MAPE is estimated in absolute terms, it can be averaged over time frames to provide a sense of how well the fitted model predicts the historical values in relation to of choices for the fitted model. MAPE closest to 0 indicates less error in the prediction. The MAPE for the fitted model based on 1948 – 2016 is 1,071. The MAPE for 1980 – 2016 is 32 and for 1980 – 2010 is 38. This finding leads the analyst to conclude that 1980 – 2016 is the best choice for seed data in the uranium price forecast.

The fitted model that best fits seed data from 1980 – 2016 is called Brownian Motion Mean Reversion (BMMR). It is a stochastic process that when given an initial value randomly chooses the value for the next period based on the estimated parameters of the process. Because it is a stochastic process, each time the BMMR is simulated, with the same initial starting value, alternative pathways result because of randomness. Figure A1– 9 shows in red a sample path for the BMMR given the uranium price in 1980. In simulation thousands of sample paths are generated. The light gray area in the figure indicates the 95% confidence interval from the simulated data, and the dark gray area indicates the 75% confidence interval. The figure illustrates that almost all of the historical observations fit within the 95% confidence interval, with the noted exception of the 2008 energy price spike. The sample mean is given as a solid black line. It shows a relatively constant value across time. This is because, in the BMMR process, observations tend towards a central mean. In the figure, the mean of the simulated observations is $82.02.

The BMMR becomes the model used to forecast uranium prices. Figure A1– 10 shows the price forecast through the end of the century. The mean of the observations is represented by the solid blue line in the center of the figure. It increases then levels off because of the mean reversion characteristic of the fitted model. Because the simulation produces a distribution of possibilities in each year, additional statistics about the forecast are provided. The 90% and 10% lines indicate where 80% of the observed values in simulation resulted. The average value for the 10% line is $28.74 and for the 90% line is $134.41. The mean value, the solid blue line, across the simulation is $81.61.

The mode, the red line shown with variation, plots the mode from the distribution in each year. The most frequently occurring value in a distribution, the mode is a useful statistic to answer the question of what is the “most likely” value to expect in a given year. While the mean shows a constant value, the mode illustrates what the volatility in uranium prices might look like through the end of the century.

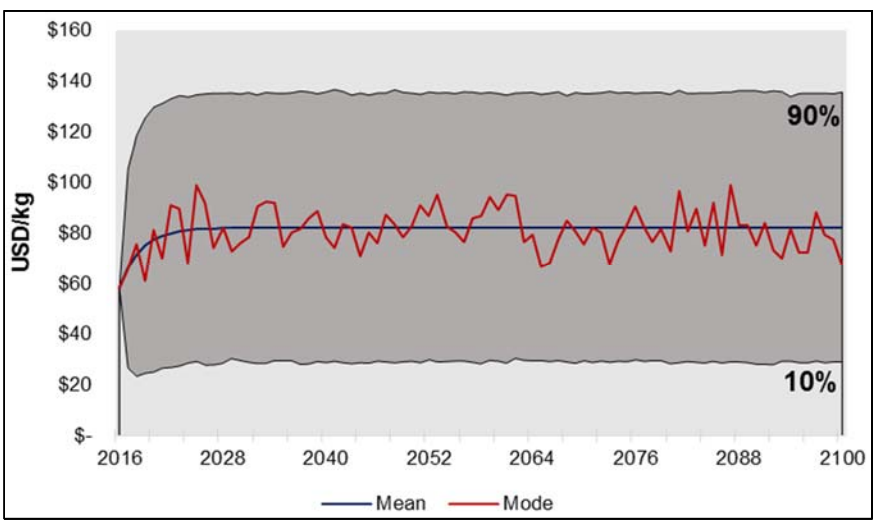


Figure A1– 10 Uranium price forecast using Brownian motion mean reversion time series model based on historical uranium prices from 1980 – 2016 in constant 2016 dollars.

Coupled with Figure A1– 10, Table A1– 5 provides statistics form discrete intervals with in the simulation. Representing possibilities for uranium 10 years out, 25 years out, 50 years out, and through the end of the century, the table provides the statistics that are illustrated in Figure A1– 10. The table show statistics by year in two formats, “In Year” and “Up to Year.” The In Year statistics come from the distribution of possibilities for the year indicated. The Up To Year statistics represent what one might expect leading up to the year indicated. Notice the tighter confidence intervals and smaller standard deviation in the Up To Year statistics. This results because of the law of central tendency. Because the distributions from each year are averaged to compute the Up to Year statistics, the resulting distribution is more narrow (i.e. has less uncertainty) than the distribution of a single year.

Table A1– 5 Summary statistics of uranium price forecast by year and up to year.

Year(s)	Mean	Mode	Std Dev	10%	90%
In 2027	$81.75	$91.91	$41.55	$27.81	$134.89
Up to 2027	$77.42	$85.04	$24.20	$46.35	$108.47
In 2042	$82.19	$74.26	$41.67	$29.29	$136.58
Up to 2042	$80.24	$74.41	$17.19	$58.33	$102.25
In 2067	$82.20	$67.91	$41.49	$29.19	$135.08
Up to 2067	$81.22	$83.86	$12.70	$64.93	$97.62
In 2100	$82.20	$77.46	$41.40	$29.07	$134.93
Up to 2100	$81.61	$82.38	$10.03	$68.84	$94.44

Figure A1– 11 illustrates how the central tendency across simulation years narrows the distribution over a single year. The blue histogram in the figure results from the distribution in year 2100. The red histogram is the average of the distributions from years 2017 up through 2100. Averaging 83 distributions leads to the more narrow result. Another conclusion that can be taken from this result is that, based on the time series analysis of historic uranium prices, one can expect that over the century uranium prices will tend to oscillate around the $82.

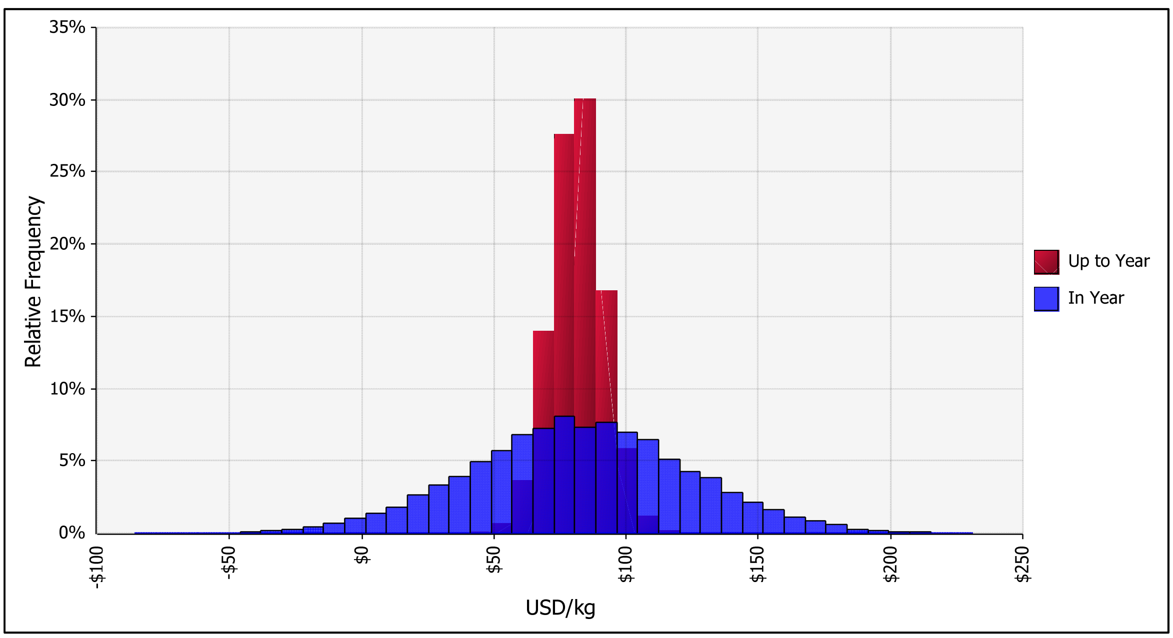


Figure A1– 11 Histogram of uranium prices in year 2100 and up to year 2100.

A1-6.3 Definition of Uranium Reserves

The definitions of the conventional resource categories as established by the IAEA are as follows:

Reasonably Assured Resources (RAR) refer to uranium 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.

Inferred Resources (before 2008 Estimated Additional Resources Category I (EAR-I)) refer to uranium 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 but 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.

Prognosticated Resources (before 2008 Estimated Additional Resources Category II [EAR-II]) refers to uranium in addition to inferred resources 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 inferred resources.

Speculative Resources refer to uranium, in addition to Prognosticated Resources, that is thought to exist, mostly on the basis of indirect evidence and geological extrapolations, in deposits discoverable with existing exploration techniques. The location of deposits envisaged in this category could generally be specified only as being somewhere within a given region or geological trend. As the term implies, the existence and size of such resources are speculative.

Unconventional Resources are considered very low-grade resources, which are now not economic or from which uranium is only recoverable as a minor by-product (phosphates, monazite, coal, lignite, and black shale).

The IAEA in its biennial *Red Book* (OECD 2008) also uses the convention of Identified Resources (before 2008 Known Conventional Resources) that consist of RAR and Inferred Resources, recoverable at a cost of less than \$130/kgU (<\$50/lb U_3O_8) USD. Undiscovered Resources consists of Prognosticated and Speculative Resources (SR).

Special note on U.S. reserves: The U.S. does not report EAR-I and EAR-II (Inferred and Prognosticated) quantities separately, but rather combines and reports them as EAR-II only. IAEA also uses the following cost categories for uranium resources.

<\$40/kgU (<\$15.38/lb U_3O_8)

<\$80/kgU (<\$30.77/lb U_3O_8)

<\$130/kgU (<\$50.00/lb U_3O_8)

Thus the combination of implied resource availability and cost defines the expectations for recovered reserves within a given price expectation.

A1-6.4 World Reserves of Uranium

The IAEA *Red Book 2007* estimated world reserves are as shown in Table A1– 6. Changes from *Red Book 2005* values are noted in italics (OECD 2006a, OECD 2008). This data is displayed graphically in Figure A1– 12. The right-hand scale in the figure maps the resource amount to the years of supply it represents were annual demand to remain at late-2000s consumption levels of about 67,000 tU/year. If one assumes that all uranium sources are captured in the *Red Book* estimates, then, Identified Resources at less than $80/kgU will suffice for 70 years and the resource base represents approximately 240 years of supply.

Table A1– 6 Red Book 2007 Known World Uranium Resources and changes from Red Book 2006 (italics) (1000 tU).

	Cost Category				
Resource Category	$0–40/kgU	$40–80/kgU	$0–80/kgU	$80–130/kgU	$0–130/kgU
Reasonably Assured Resources	1,766 *(-181)*	832 *(+136)*	2,598 *(-45)*	740 *(+86)*	3,338 *(+41)*
Inferred Resources	1,204 *(+405)*	654 *(+292)*	1,858 (+697)	272 *(-13)*	2,130 *(+684)*
Total Identified Resources	2,970 *(+224)*	1,486 *(+428)*	4,406 *(+652)*	1,012 *(+74)*	5,469 *(+726)*
Prognosticated Resources	—	—	1,946 *(+246)*	823 *(+4)*	2,769 *(+250)*
Speculative Resources (SR)	—	—	—	—	4,797 *(+240)*
					*2,973 *(-6)*
Total Undiscovered Resources	—	—	1,946 *(+246)*	—	7,770 *(+234)*
All Conventional Resources	2,970 *(+224)*	—	6,349 *(+898)*	—	13,035 *(+1,216)*
[a]Unconventional Resources**	—	—	—	—	
- From Phosphates					22,000
- Seawater					4,000,000

“t” is metric tonne.
* Cost range unassigned
** Phosphate recovery has been estimated at USD 60–100/kgU including capital investment, and seawater extraction has been estimated in the order of USD 300/kgU
a. 2005 data.
Not all countries report separate figures for the two lowest cost categories.
The figures are adjusted to account for mining and milling losses.

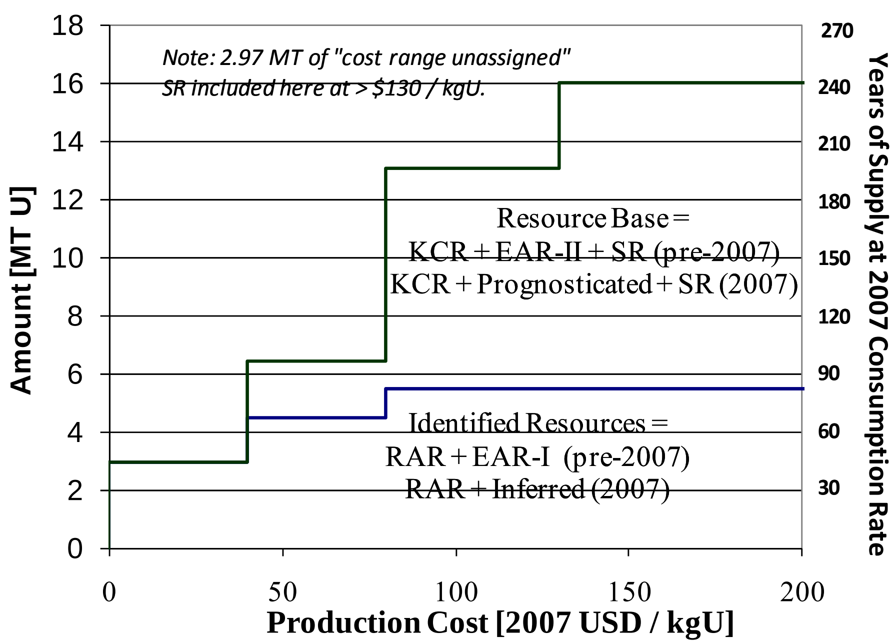


Figure A1– 12 Graphical depiction of Red Book supply estimates.

Table A1– 7 shows that the world reserves of uranium are dominated by foreign supply.

Table A1– 7 Known recoverable resources of uranium.[a]

Country	Tonnes U	Percentage of World
Australia	1,216,000	27%
Kazakhstan	751,600	17%
Russian Fed.	495,400	11%
Canada	423,200	9%
South Africa	343,200	8%
Brazil	231,000	5%
Namibia	230,300	5%
USA	99,000	2%
Uzbekistan	86,200	2%
World Total	4,456,000	
a. Reasonably Assured Resources plus Inferred Resources to U.S.$80/kgU, from OECD NEA & IAEA, *Uranium 2007: Resources, Production and Demand.*		

The World Nuclear Association (WNA) (WNA 2009) interprets these data to imply that "the world's present measured resources of uranium (5.5 Mt) in the cost category somewhat below present spot prices and used only in conventional reactors, are enough to last for over 80 years. This represents a higher level of assured resources than is normal for most minerals. Further exploration and higher prices will certainly, on the basis of present geological knowledge, yield further resources as present ones are used up." The *Red Book* authors reinforce this point, noting that "[t]he uranium resource figures presented here are a 'snapshot'… and are not an inventory of [the] total amount of mineable uranium contained in the Earth's crust. Should favourable market conditions continue to stimulate exploration additional discoveries can be expected…" (OECD 2008). *Red Book* supply estimates are fluid, with new discoveries that increase the resource base offsetting extraction activities that reduce it. Figure A1– 13 shows that from 1965 to 2007, *Red Book* Identified Resources increased by approximately 2 million tU, even as 2 million tU were extracted. Therefore, about 4 million tU was added to the Identified Resource base during this time period.

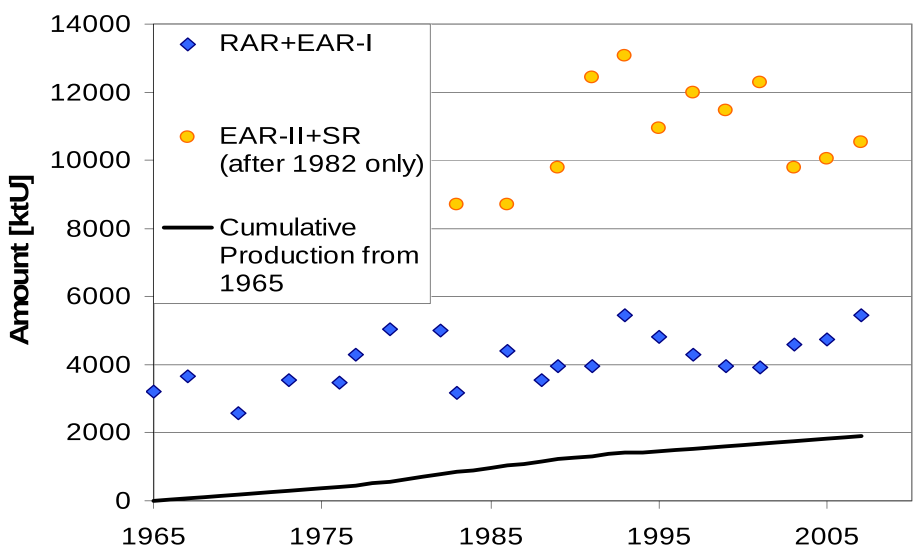


Figure A1– 13 Cumulative uranium production, Red Book Identified (RAR+EAR-I) Resources and Resource Base, 1965-present.

Much of what is known about the existence of uranium reserves is the result of a single cycle of exploration-discovery-production that was driven in large part by peak prices for uranium in the late 1970s. Little exploration has occurred from the early 1980s to the mid 2000s. As has been seen, that initial cycle provided enough uranium to last for over 3 decades (see Figure A1– 15). The uranium price boom of the mid to late-2000s has fostered a second wave of intensive exploration. A strong increase in world uranium exploration expenditures (Figure A1– 14 [OECD 2008]) has contributed to the 1.2 million tonne increase in the uranium resource base of the 2007 *Red Book* as compared to 2005. Exploration expenditures may be placed in perspective if it is noted that the historical average cost of resource discovery has been $2/kgU (OECD 2008). Then the 2005–2006 exploration expenditures, which totaled around US $1.5B, show that prospecting is continuing to yield discoveries that match or even surpass historical norms.

Domestically, the U.S. Energy Information Administration reports that domestic uranium exploration and development expenditures increased from an average of $5M/year during the 1999–2001 time period to $18.1M in 2005, $40.1M in 2006, $67.5M in 2007, and $81.9M in 2008. Large exploration expenditure increases are also being seen in Canada and Kazakhstan; the *Red Book* indicates worldwide exploration expenditures of about $400M in 2005. Given that, historically each $3 of exploration expenditures has led to the production of 1-pound U_3O_8 (Pool 2006), the current supply tightness may be expected to ease.

It is important to note that it takes some time for a successful prospecting claim to become an operational mine. For mines that opened in 1999–2001, the elapsed time between discovery and commencement of mining was 20 years (OECD 2006b). On the other hand, the corresponding time interval for mines that opened between 1970 and 1980 was under 10 years. While an increased regulatory burden and local public opposition may account for a component of this increase, it is likely that the unfavorable economics—from a seller's perspective—of the uranium business accounted for many discoveries remaining untapped through the 1990s. Therefore, it is reasonable to claim 10–15 years as a realistic prospecting-to-production time delay.

Discoveries and mine openings in the U.S. will be addressed later in this section.

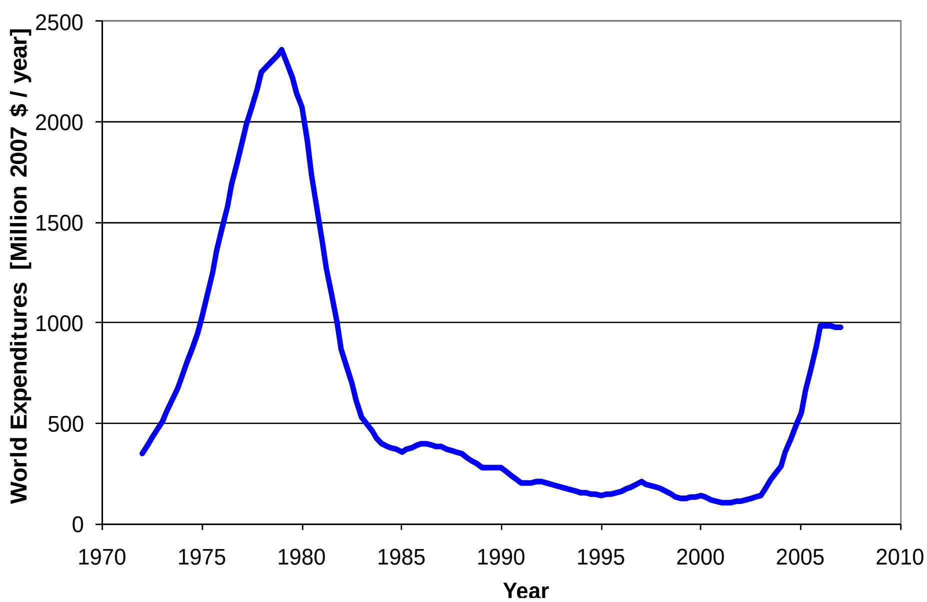


Figure A1– 14 Worldwide annual uranium exploration expenditures, 1972-present.

Figure A1– 15 depicts an evaluation of the abundance of uranium in the earth's crust by K. S. Deffeyes and I. D. MacGregor. The Figure A1-15 shows many of the recognized source materials from which uranium can be recovered. As with other metals and energy-related commodities, such as oil and gas, focused exploration could be expected to expand known resources. WNA further states that "a doubling of price from present levels could be expected to create about a tenfold increase in measured resources, over time" (EPA 1995).

This WNA statement may be inferred from Figure A1-15 with the aid of a simplifying assumption. If one assumes that, to first order, the cost of extracting and purifying a unit mass of ore is independent of grade, then the cost of producing a kilogram of uranium would be inversely proportional to the ore grade. Looking at the region of Figure A1-15 labeled "Current Mines," one sees that a reduction of an order of magnitude in ore grade would lead to a three order of magnitude increase in the availability of uranium at that lower ore grade. For example, referring to Figure A1– 15 one sees that 10^5 tonnes of uranium are estimated to exist in deposits having grade 10,000 ppm or higher. Moving to ores one order of magnitude less rich, 1,000 ppm, the estimated availability increases by three orders of magnitude to 10^8 tonnes. Hence, if the production cost is indeed inversely proportional to grade, and no other factors affecting the price are considered, the ore grade distribution of uranium deposits does indeed imply that a doubling of price would increase the economically extractable amount of uranium by about a factor of 10. Other forecasters have applied somewhat different assumptions and interpretations of Figure A1– 15 to arrive at slightly different conclusions (Schneider 2005). It must be noted that these estimates do not take into account that factors discussed below that have seen most mineral prices decline over the past century.

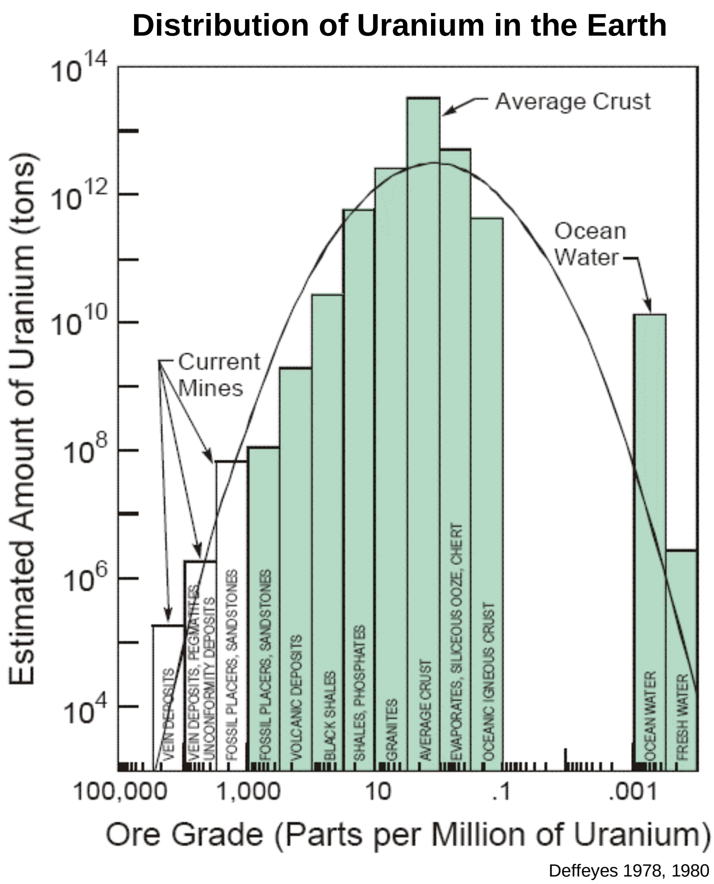


Figure A1– 15 Distribution of uranium in the earth (Deffeyes and MacGregor 1980).

Without constraint by cost, the total resource base reported by IAEA-NEA (Known Conservative Resources with Undiscovered Conventional Resources) represent 16.0 million tonnes, which is almost a 300-year supply at today's rate of consumption by light water reactors. If unconventional resources, such as phosphate deposits (22 MT) and seawater (up to 4000 MT), which would cost two to six times the present market price to extract, are considered, the supply becomes essentially unbounded. Uranium extraction as a by-product of phosphate mining, where tailings contain 50–200 ppm U, has historically been achieved with costs ranging from $22–54 per lb U_3O_8 (Wise Uranium Project 2008). Higher prices for supply will drive further exploration. As exploration expands, more geologic knowledge is gained of existing or new deposits and typically new technologies developed to cost effectively utilize the resource. The recent history of the Athabasca Basin in Canada suggests that the largest proportion of future resources will be as deposits discovered in the advanced phases of exploration. It is clear that a combination of mineral exploration and development of technology advances will need to generate economical resources at least as fast as they are being consumed.

Granted that a large supply of crustal uranium is theoretically available, the issue of the economic viability of lower-grade deposits that might be mined in the future remains controversial and unresolved. In the absence of industrial experience or detailed bottom-up studies of such operations, a surrogate measure of their cost has been devised. This is the concept of the cutoff ore grade. Extending beyond uranium to other minerals, it postulates that there exists an ore grade below which the energy input to the mining process alone makes the extraction cost prohibitive.

For uranium, the cutoff grade is typically defined as the grade at which the energy consumed in mining exceeds some threshold fraction of the energy produced by the nuclear power cycle. Chapman (1975) pioneered the investigation of the uranium cutoff grade. He calculated the ore grade at which the nuclear power cycle becomes endothermic to be around 20ppmU (Prasser et al. 2008). Extraction energy and production cost are closely coupled, and there is no doubt that (due primarily to overburden haulage) an inverse relationship exists between ore grade and energy requirements per unit uranium produced. Chapman and successors estimate this cutoff grade by summing the energy inputs associated with each step shown in Figure A1– 16. Note that in-situ leaching, a new technique that was in its infancy when Chapman wrote, bypasses waste rock haulage.

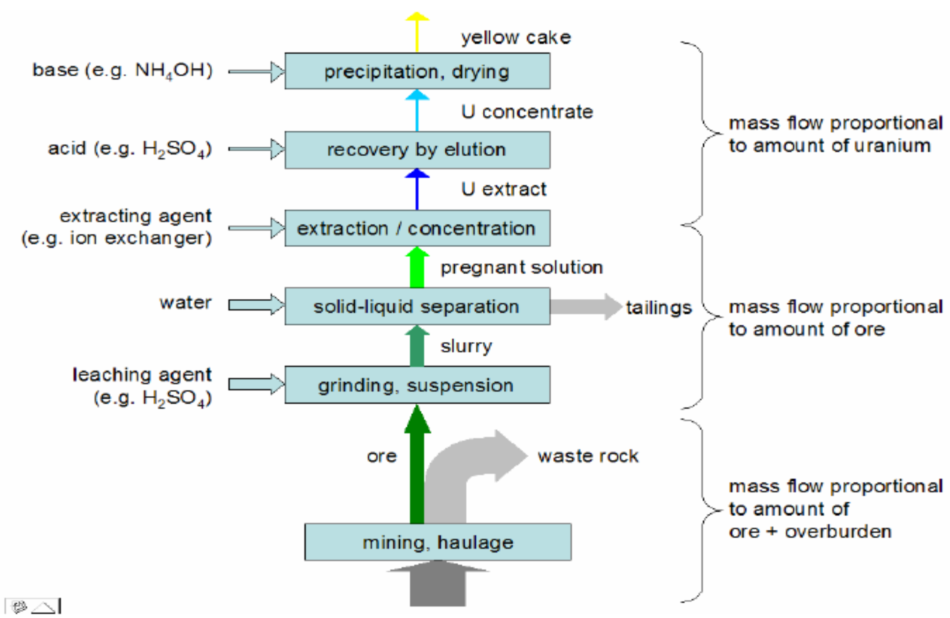


Figure A1– 16 Mass flow through the uranium mining and milling process (from Prasser et al. 2008).

Chapman and others derived cutoff grade estimates by extrapolating energy consumption data trends from existing mines to low ore grades. A great deal of additional data, some for mines operating with low grade ore, has accumulated since Chapman's pioneering work. Smith and Storm van Leeuwen (SSL) used extensive data relating ore grade to energy consumption collected in the 1970s and 1980s to refine Chapman's analysis. Assuming a reciprocal relationship between ore grade and energy requirements and including energy inputs elsewhere in the fuel cycle (e.g. decommissioning), they predicted a much higher breakeven grade—between 100 and 200 ppm—implying exhaustion of viable uranium by 2050 if nuclear power grows at 2.5% per year from 2008 (Storm van Leeuwen and Smith 2005). This result implies that even some of the reserves identified in the *Red Book* will prove prohibitively expensive (as measured by mining energy consumption, or equivalently monetary cost) to extract.

Prasser et al. used newer data for mines operating at lower grade (e.g., Rossing, 250 ppm) and/or using in-situ leaching (ISL) to create another estimate of the cutoff grade. Prasser discarded the assumed reciprocal ore grade, energy relationship of SSL, and instead used the newer data to fit a more general functional relationship. Prasser's work therefore also extends to ISL facilities with low stripping ratios. The stripping ratio, S, is defined as (ore mass + waste mass)/(ore mass) (i.e., no overburden or ore haulage). His results, along with those of SSL, are shown in Figure A1– 17.

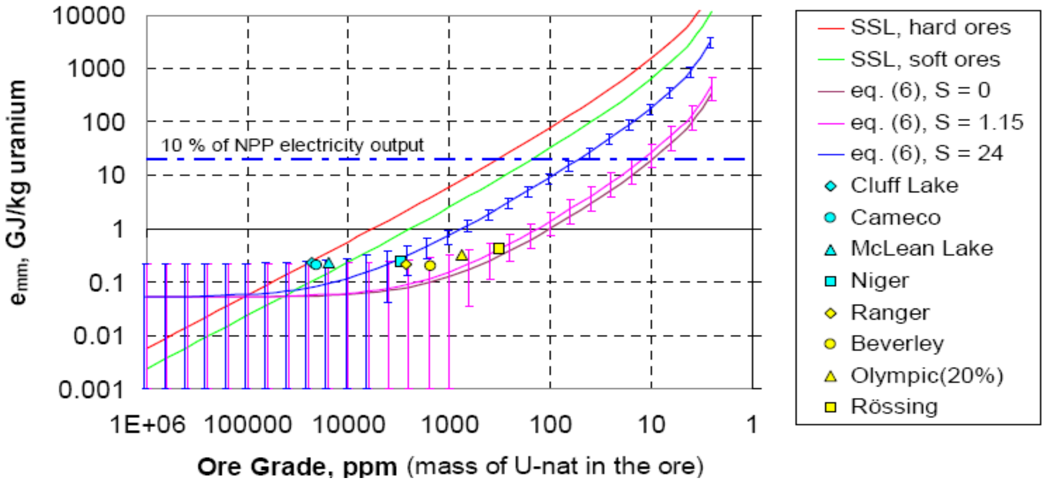


Figure A1– 17 Ore Grade versus mining energy input estimates of Smith and Storm van Leewen (SSL) and Prasser. Figure source: Prasser 2008.

Data points from existing mines are superimposed upon the forecasts of SSL and Prasser. Prasser's three sets of results correspond to underground mining of high-grade sandstone deposits (S = 24), lower-grade open-pit projects such as Rossing (S = 1.15) and ISL or surface leaching of existing tails piles (S = 0). Using a practical variant of the cutoff grade definition (i.e., extraction would be impractical if the energy input exceeded 10% of eventual power output) the cutoff grade is seen to range from 200 to 300 ppm (SSL), to 50 ppm (Prasser, high overburden mines), to 10 ppm (Prasser, low overburden mines).

These forecasts correspond to a vast range of economically attractive uranium reserves: from less than the *Red Book* currently estimates (SSL) to orders of magnitude more (Prasser). Prasser's model evidently provides a much better fit to existing data for low-grade mines, but estimates based upon extrapolation from existing data—all *a priori* forecasts of the cutoff grade rely upon this technique—must be used with caution.

Hubbert peak theory has been used to support the claim that scarcity of uranium supply is imminent. The theory states that all nonrenewable resources will obey a trajectory in which a peak global extraction rate is reached, followed by a terminal decline. Therefore, cumulative temporal mineral extraction histories plotted versus time will obey a logistic or S-shaped function. It is difficult to observe this peak or prove its existence statistically until after it has passed. Some evidence may be interpreted to imply that this peak may indeed have passed for uranium. One study claims that some early leaders in uranium extraction have passed the peak production that can be supported by their own resource base. In France and the United States, uranium production began in the 1950s, peaked in the 1980s (at 3 ktU/year and 20 ktU/year respectively), and has since declined drastically (in the U.S. by over 90%; in France production has ceased altogether). Proponents of an imminent or already-passed uranium Hubbert peak assert that attractive deposits having been depleted in these nations, the same phenomenon can be expected to occur elsewhere in the near-term (Energy Watch Group 2006). Others claim that declining demand following the late-1970s boom and discovery of inexpensive resources elsewhere simply pushed the marginal French and U.S. operations into obsolescence.

A1-6.5 U.S. Reserves of Uranium

Details on the U.S. uranium reserves by state are provided in Table A1– 8 with geographical locations shown in Figure A1– 18 and Figure A1– 19. The U.S. potential uranium resources by forward-cost category and resource region are included in Table A1– 9. The U.S. uranium mine production and number of mines and sources for the period of 1995–2008 is provided in Table A1– 10.

Table A1– 8 U.S. reserves of forward-cost uranium by state (December 31, 2003)

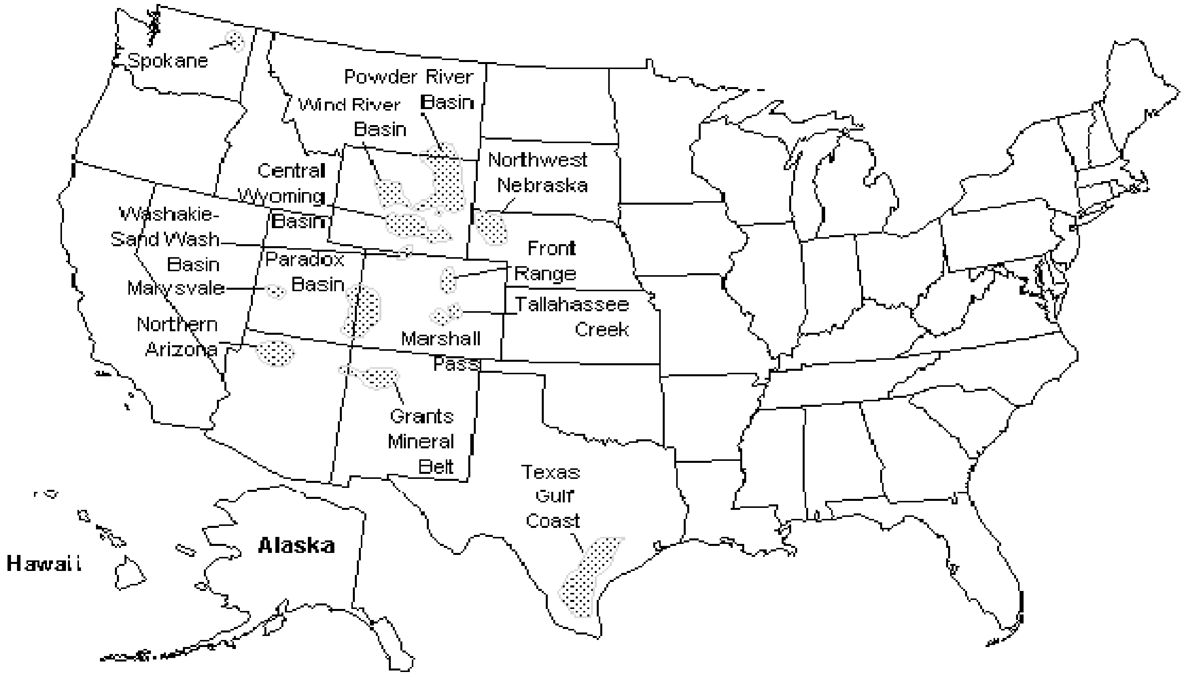
	$30 per pound			$50 per pound		
State(s)	Ore (million tons)	Grade[a] (percent U_3O_8)	U_3O_8 (million pounds)	Ore (million tons)	Grade[a] (percent U_3O_8)	U_3O_8 (million pounds)
Wyoming	41	0.129	106	238	0.076	363
New Mexico	15	0.280	84	102	0.167	341
Arizona, Colorado, Utah	8	0.281	45	45	0.138	123
Texas	4	0.077	6	18	0.063	23
Other[b]	6	0.199	24	21	0.094	40
Total	74	0.178	265	424	0.105	890

a. Weighted average percent U_3O_8 per tonne of ore.

b. Includes California, Idaho, Nebraska, Nevada, North Dakota, Oregon, South Dakota, and Washington.

Notes: Uranium reserves that could be recovered as a by-product of phosphate and copper mining are not included in this table. Reserves values in forward-cost categories are cumulative; that is, the quantity at each level of forward cost includes all reserves at the lower costs. Totals may not equal sum of components because of independent rounding.

Sources: Estimated by Energy Information Administration, Office of Coal, Nuclear, Electric and Alternate Fuels, based on industry conferences; U.S. Department of Energy, Grand Junction Office, files; and Energy Information Administration, Form EIA-858, "Uranium Industry Annual Survey," Schedule A, Uranium Raw Material Activities (1984–2002) and Form EIA-851A, "Domestic Uranium Production Report," (2003).



Sources: Based on U.S. Department of Energy, Grand Junction Project Office (GJPO), National Uranium Resource Evaluation, Interim Report (June 1979) Figure 3.2; and GJPO data files.

Figure A1– 18 Major U.S. uranium reserve areas.

Figure A1– 19 Uranium resource regions of the U.S.

Table A1– 9 U.S. potential uranium resources by forward-cost category and resource region (million pounds U3O8).

Resource Region	Forward-Cost Category: $30 per pound EAR[a]	SR[b]	$50 per pound EAR[a]	SR[b]	$100 per pound EAR[a]	SR[b]
Colorado Plateau	1,330	480	1,900	770	2,540	1,210
Wyoming Basins	160	80	340	160	660	250
Coastal Plain	370	130	490	180	600	230
Northern Rockies	30	110	60	200	170	300
Colorado and Southern Rockies	140	90	180	140	220	190
Basin and Range	50	90	160	170	390	320
Other Regions[c]	110	330	180	610	270	990
Total	2,190	1,310	3,310	2,230	4,850	3,490

a. EAR = Estimated Additional Resources.

b. SR = Speculative Resources.

c. Includes Appalachian Highlands, Great Plains, Pacific Coast and Sierra Nevada, Central Lowlands, and Columbia Plateau regions, and Alaska.

Notes: Values shown are the mean values for the distribution of estimates for each forward-cost category, rounded to the nearest 10 million pounds U_3O_8. Estimates of uranium that could be recovered as a by-product of other commodities are not included. Resource values in forward-cost categories are cumulative; that is, the quantity at each level of forward cost includes all resources at the lower cost in that category.

Sources: Prepared by the Energy Information Administration, Office of Coal, Nuclear, Electric and Alternate Fuels, based on uranium resources data developed under DOE National Uranium Resource Evaluation (NURE) program and the USGS Uranium Resource Assessment project, using methodology described in Uranium Resource Assessment by the Geological Survey: Methodology and *Plan to Update the National Resource Base*, U.S. Geological Survey Circular 994 (1987).

Table A1– 10 U.S. uranium mine production and number of mines and sources, 1995-2008.

Mining Method	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
Underground														
(metric tonnes U)	0	W	W	W	W	W	0	0	W	W	W	W	W	W
Open Pit														
(metric tonnes U)	0	0	0	0	0	0	0	0	0	0	0	0	0	0
In situ Leaching														
(metric tonnes U)	1,297	1,684	1,571	1,431	1,473	1,152	W	W	W	W	1,031	1,638	W	W
Other[a]														
(metric tonnes U)	60	125	241	408	276	49	W	W	W	W	W	W	W	W
Total Mine Production														
(metric tonnes U)	1,357	1,810	1,812	1,840	1,750	1,201	1,018	925	[E]846	961	1,171	1,804	1,747	1,492
Number of Mines Operated														
Underground	0	1	1	4	3	1	0	0	1	2	4	5	6	10
Open Pit	0	0	0	0	0	0	0	0	0	0	0	0	0	0
In situ Leaching	5	6	7	6	6	4	3	3	2	3	4	5	5	6
Other Sources[b]	7	6	6	5	5	5	4	3	1	1	2	1	1	1
Total Mines and Sources	12	13	14	15	14	10	7	6	4	6	10	11	12	17

a. For 1995, "Other" includes production from uranium-bearing water from mine workings and restoration. For 1996–2000, "Other" includes production from underground mines and uranium-bearing water from mine workings and restoration.

b. "Other Sources" includes, in various years, heap leach, mine water, mill site cleanup and mill tailings, well field restoration, and low-grade stockpiles as sources of uranium.

W=Data withheld to avoid disclosure. The data are included in the total for "Other" through 2000.

E=Estimate to avoid disclosure of individual company data.

Notes: Totals may not equal sum of components because of independent rounding. Table does not include by-product production and sources.

Sources: Energy Information Administration: 1993–2001-Uranium Industry Annual 2001 (May 2002). 2002-Form EIA-858, "Uranium Industry Annual Survey;" Schedule A: Uranium Raw Material Activities; Energy Information Administration: Form EIA-851A, "Domestic Uranium Production Report" (2003–2008).

A1-6.6 Market Price for Uranium

Figure A1– 20 presents uranium supply curves constructed from data in the 2011 OECD Nuclear Energy Agency/International Atomic Energy Agency *Redbook* (OECD 2010, 2011). Total identified and speculative resources have both increased from 2009[d]. The analogous data from the *2009 Redbook*, depicted by the dashed lines in Figure A1– 20, shows that lower-cost resources – at $130/kg U and below – have declined (the solid line is left of the dashed line), but the increase in resources producible at $260/kg U and above has more than compensated. Along with new discoveries, extraction operations at active lower-cost mines as well as reclassification of as yet untapped deposits into higher cost bins have contributed to this shift.

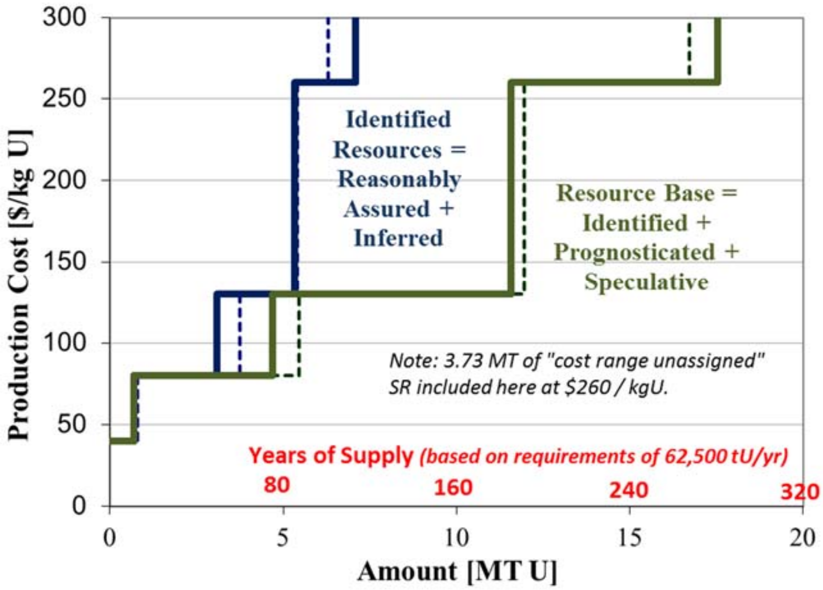


Figure A1– 20 2011 (solid) and 2009 (dashed) Redbook uranium supply curves. [e]

"Identified Resources" stood at 6.31 million tonnes U (MTU) in the 2009 *Redbook* and 7.10 MT in 2011. This increase of 790,000 tonnes U (tU) through 2009 and 2010 represented more than ten years' production at current rates and took place even as 105,000 tU were produced. Ref. [1] cited a boom in exploration induced by higher uranium prices beginning around 2005 as the major driver of this increase.

But the increase is not unprecedented or unusual: since the *Redbook* began publication in 1965, the identified uranium resource pool has risen steadily. Figure A1– 21 shows that identified resources have more than doubled from 3.2 MTU in 1965 to 7.1 MTU in 2011 even though nearly 2.1 MTU of uranium was mined during the same period.

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[d]. See the 2009 CBR for definitions of supply categories, discussion of the domestic supply picture, and a review of secondary supply sources.

[e]. In the pre-2007 Redbook classification scheme, RAR = reasonably assured resources, EAR-I and II = estimated additional resources in Categories I and II, with Category II being less certain than Category I, and SR – speculative resources.

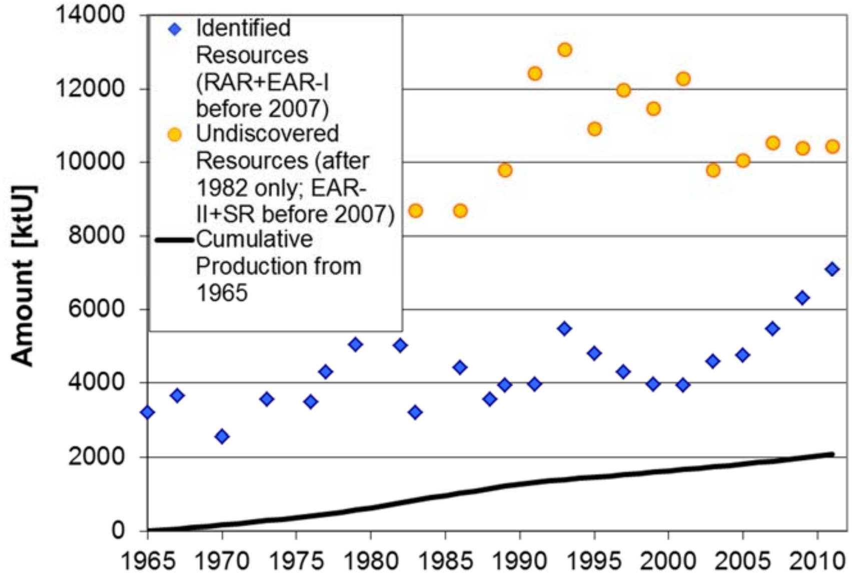

Figure A1– 21 Cumulative production and Redbook resource estimates since 1965.

Following an extended period of depressed prices through the 1990s and early 2000s and a sharp boom from 2005-2008, a measure of stability returned to the uranium market during 2009-12. Figure A1–22 shows that both the spot and long-term delivery prices remained near their mid-2012 levels of \$50/lb U_3O_8 (\$130/kg U) and \$60/lb U_3O_8 (\$156/kg U), respectively, throughout the period. Most uranium transactions are handled through long-term contracts. The long-term price in the figure assumes a delivery time frame of at least 2 years as well as terms often present in contracts such as an allowance for flexibility in the quantity actually purchased. As such, while spot prices are a leading indicator of contract prices, a gap between the two may persist even when the market is near equilibrium conditions.

Figure A1– 22 UxC uranium spot (solid) and long-term (dashed) prices, 2009-12. Figure source: the Ux Consulting Company, LLC, http://www.uxc.com.

Because the supply of newly generated uranium is controlled by the world market and dominated by foreign supply, the future price for U.S. supply would expect to meet that world market price. IAEA-NEA in its analysis of uranium supply evaluated cumulative supply and demand for uranium to 2050 (IAEA 2001). The study considered the reality of reducing existing inventories, the infusion of prior weapons HEU into the market, as well as other significant secondary supply market impacts. Three demand cases were evaluated (low, middle, high) and covered scenarios from phase out of nuclear power in 2100 in the low case to high economic growth and significant development of nuclear power in the high case. The middle was simply the mid-point of the two cases. Cumulative uranium requirements ranged from 3,390 to 7,577 MTU. Production from high confidence RAR was projected to be adequate in the low demand case. Deficits arise when considering use of low cost supplies to meet the middle and high cases. The study, therefore, estimated the year in which uranium from higher cost production could be justified. Table A1– 11 is a summary of the IAEA-NEA projections.

Table A1– 11 Year when higher cost uranium production is justified (U.S. dollars) (IAEA 2001).

	\$20–30/lb U_3O_8 \$52–78/kgU	\$30–50/lb U_3O_8 \$78–130/kgU	>\$50/lb U_3O_8 >\$130/kgU
Middle-Demand Case			
RAR	2019	2024	2028
RAR + EAR-I	2021	2027	2034
RAR + EAR-II	2021	2029	2041
High-Demand Case			
RAR	2013	2019	2023
RAR + EAR-I	2015	2022	2026
RAR + EAR-II	2015	2023	2031

The years highlighted above (2034 and 2026) for the middle demand and high demand cases respectively, indicate the first year in which a deficit is projected to exist between the lower-cost (<\$130/kgU) "known resources (RAR + EAR-I)" and market-based production requirements. The timing of the deficit corresponds with a significant increase in the price of uranium. However, IAEA-NEA has speculated that if significant and timely exploration is conducted, and sufficient resources are discovered, there could be an adequate supply of lower-cost uranium to satisfy demand. If not, the demand can be met by both very high-cost conventional resources and unconventional resources, or by new lower-cost conventional resource discoveries made from speculative resources. This would require use of very high-cost conventional and unconventional resources to meet both the middle and high-demand cases.

The U.S. government does not own any currently producing uranium mines, but DOE does have inventories of secondary supplies as shown in Table A1– 12. The DOE inventory reported in the table—134.9 million lbs. of natural U_3O_8 equivalent—represents uranium of all forms declared surplus by DOE as of May 2006 (DOE 2006a) (DOE 2008a). Of this excess uranium, 55.8 million pounds is HEU to be blended to LEU; most of the rest is NUF_6 or DUF_6 "of economic value." To avoid distorting effects that would accompany large-scale dumping, DOE proposes to place on the market no more than 10% of the annual fuel requirements of the domestic reactor fleet, or about 5 million tons per year.

Table A1– 12 Inventories of natural and enriched uranium as of end of year, 1998-2007 (thousand pounds natural U3O8 equivalent).

Type of Uranium Inventory	Inventories at the End of the Year									
	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
Owners and Operators of U.S. Civilian Nuclear Power Reactors	65,758	58,250	54,804	55,636	53,461	45,639	57,665	64,729	77,484	81,227
Of which: Natural Uranium	42,051	44,761	35,952	34,433	31,029	22,674	27,889	45,339	54,251	55,927
Of which: Enriched Uranium [a, d]	23,708	13,488	18,851	21,204	22,432	22,965	29,766	19,390	23,233	25,301
U.S. Supplier Inventories [b]	70,732	68,848	56,455	48,147	48,653	39,850	37,544	29,068	29,107	31,156
Of which: Natural Uranium	35,030	29,468	12,616	9,192	W	W	W	W		
Of which: Enriched Uranium [a, d]	35,702	39,380	43,839	38,955	W	W	W	W		
Total Commercial Inventories	136,491	127,097	111,258	103,783	102,114	85,489	95,209	93,796	106,591	112,384
Excess DOE-owned Inventory	24,454	53,054	N/A	N/A	51,789	N/A	N/A	134,900	N/A	153,200

a. Includes amounts reported as inventories of enriched UF_6 at enrichment suppliers (1998–2001).
b. Includes inventories owned by the 1998 privatized USEC, Inc. (United States Enrichment Corporation).
c. DOE-owned excess inventories reported by the U.S. Department of Energy. Variations during this period largely reflect changes in DOE classification of excess materials, rather than disbursement or acquisition of uranium. See text and (DOE 2008a).
d. Enriched UF_6 and fabricated fuel not inserted into a reactor (2002–2008).
W = Data withheld to avoid disclosure.
Note: Totals may not equal sum of components because of independent rounding.
Source unless otherwise noted: Energy Information Administration, Form EIA-858, “Uranium Industry Annual Survey;” Energy Information Administration, Form EIA-858 “Uranium Marketing Annual Survey” (2003–2008).

The market price (and essentially the effective cost to the utilities) is driven by a number of key factors as follows:

Uranium Demand. Demand must consider the amount of nuclear fuel to be delivered over a given period. Relative to the nuclear market, demand is driven by the projections for economic growth driving need for power as well as the role of nuclear power in meeting the demand. Such demand can be driven by other than electricity such as a significant growth in hydrogen demand or major desalination programs. Of course, the most significant factor is the projected growth in developing nations, which will greatly influence the worldwide demand for energy. Because of such a broad range of uncertainties, demand is normally considered over a wide range of demand scenarios. Current worldwide demand requires about 68,000 MT of uranium from mines or the equivalent from stockpiles.

Supply Factors. Supply can be considered in terms of primary and secondary supplies. In the next several decades, supply will continue to be strongly influenced by the use of secondary supplies. At the beginning of this century, 42% of the worldwide demand was met by use of secondary supplies creating a buyers market and reducing the economic attractiveness of exploring for and developing new primary supplies. However, such supplies are being reduced and are under a scenario of growth of nuclear power, the gap between overall demand and that provided by secondary supply will grow, creating a stronger demand for primary supplies in the longer term.

A1-6.6.1 Spot Check on Market for Uranium

Spot prices for uranium ore (yellowcake), conversion and enrichment have all been trending downward since the Fukushima accident in 2011. The accident resulted in the temporary shutdown of all reactors in Japan and the cancellation or delay of other planned reactor construction worldwide, reducing global demand significantly. As of 2016, only 3 of the Japanese reactors have been restarted, though many others have applied for restart and are in the review process. In addition to Fukushima, other factors have also affected the individual markets. These include short-term effects of the current market supply/demand imbalances as well as some longer-term infrastructure effects. In particular, the magnitude of the price drops have resulted in some suppliers needing to dump additional products into the market to meet cash flow requirements, prolonging and deepening the downward trend in the spot market (a reinforcing loop).

Uranium prices have been descending from a speculative price peak in 2007 during the brief "nuclear renaissance" period. Prices spiked again briefly in 2011 just prior to Fukushima but have been declining since then (See Figure A1– 23).

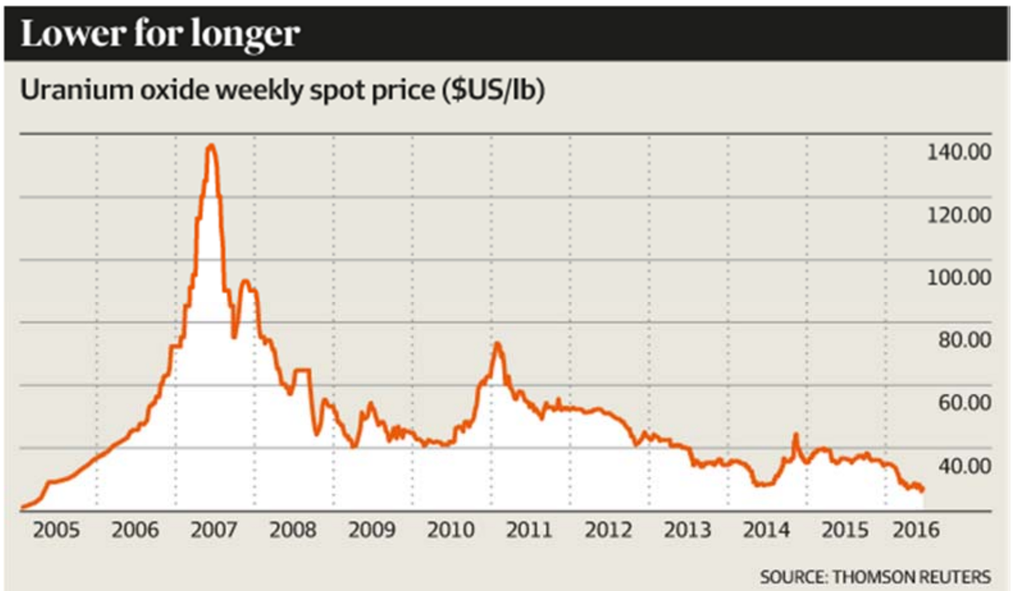

Figure A1– 23 Uranium oxide weekly spot price.

One driver suggested for the low prices [Financial Review 2016] is that producers may have been forced to sell on the spot market to improve cash positions, rather than selling primarily on the long-term market where prices are higher. Several sources have been predicting prices will stabilize because they are currently below the production cost for many producers, or that prices will rebound driven by renewed interest in nuclear energy to combat climate change.

Most uranium is purchased in longer-term contracts, so spot prices are only an indicator of the direction of the market. Price movements in the longer-term contracts tend to be smoother than the spot market and usually lag behind the spot price with respect to prolonged trends. Some longer-term contracts are fixed price while others include periodic market-related price adjustments.

Cameco Corporation provides ~18% of the world's production of uranium. Cameco targets their contract portfolio to achieve a 40:60 ratio of fixed and market-related contracts [Cameco 2016]. (A market-related contract adjusts periodically based on a formula related to current market prices, similar to a variable rate mortgage.) Table A1– 13 indicates how they predict the price they receive for their existing long-term uranium contracts would change going forward based on their portfolio as of June, 2016. Note that they do not include prices significantly lower than the current ~$25 price, implying the market may be near a bottom.

Table A1– 13 Expected realized uranium price sensitivity under various spot price assumptions [Cameco 2016]

Spot prices ($US/lb U_3O_8)	$20	$40	$60	$80	$100	$120	$140
2016	41	43	49	54	60	66	71
2017	38	45	56	68	79	88	96
2018	39	46	58	69	80	89	97
2019	38	47	58	69	79	87	94
2020	42	49	59	70	79	86	92

At the end of August, 2016, the spot price was $25.25 per lb U_3O_8 [UxC 2016]. This converts to $65.64 per kgU, which is within the range from the 2015 update of the CBR (low $32, mode $79, mean $128, high $273/kgU). See Figure A1– 24. Given the short-term uncertainty in the market, the intermediate term historic trend downward, and the projections for prices to stabilized or increase, we see no reason at this time to change the suggested price range for the CBR.

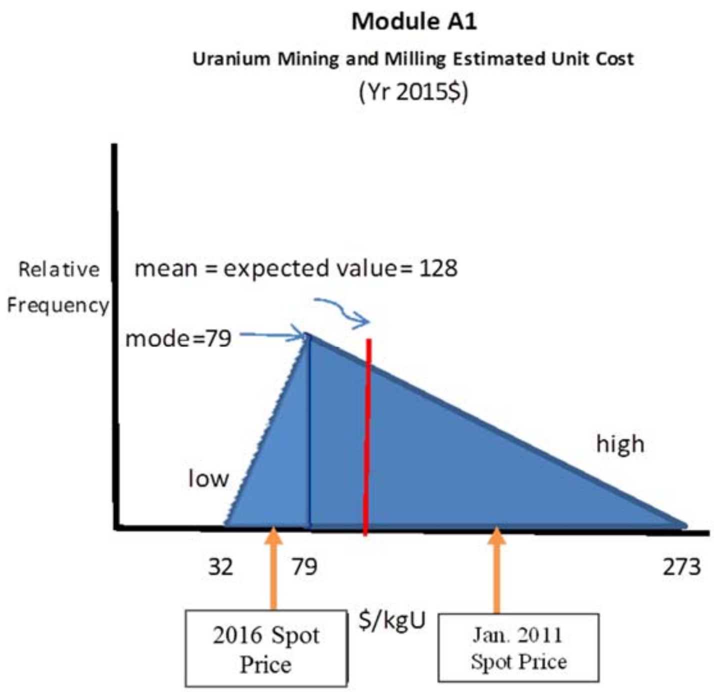

Figure A1– 24 Uranium Cost Range in 2015 CBR showing current and pre-Fukushima spot prices

A1-6.7 Secondary Supplies

Existing Inventories. Inventories of natural uranium and LEU are currently owned by uranium suppliers, United States Enrichment Corporation (USEC), utilities, and DOE. Other nations, especially Russia, also have significant inventories. Depending on short-term needs and opportunity for profit, such inventories are released into the market place (at or near market price).

Highly Enriched Uranium. Following the cold war, the United States and Russia declared large quantities of HEU and plutonium as surplus for national defense purposes (see Module C2 for details and implementation of the agreement). While other nations such as China, France, and the United Kingdom have similar materials, the market impact is basically dominated and controlled by agreement between the U.S. and Russia, who are believed to hold over 95% of the HEU stocks dedicated to nuclear weapons. In

1993, an agreement was made with Russia that 500 tonnes of Russian HEU would be converted to roughly 150,000 tonnes of LEU over a 20-year period to be used in the U.S. market. Such an amount represents roughly 50% of the U.S. utilities requirements during this period. Basically, USEC exchanges natural uranium for down-blended LEU, effectively contracting Russia (Tenex) for the cost of enrichment. The LEU is sold through USEC and a consortium of three Western companies (Cameco, Cogema, and RWE Nukem). The equivalent natural uranium feed is returned to the Russians, who can sell it or return it to Russia. In the U.S., DOE programs plan to down-blend an additional 145 tonnes of HEU for commercialization.

MOX Use. Although not currently used by the U.S. market, the world demand for uranium is influenced by the amount of plutonium/uranium MOX fuel that is to be used as the energy content of the plutonium replaces the demand for natural uranium. Use of MOX represents less than 4% of the overall equivalent uranium demand. Should U.S. policy be revised to encourage MOX use in the U.S., there would be a small but significant impact as MOX use is increased. The agreement between the U.S. and Russia to disposition surplus plutonium from the weapons programs at this point is not large enough to produce any significant impact in the overall demand.

RepU. Reprocessed uranium can be used as a direct substitution for newly generated uranium in fuel fabrication. As with MOX, the acceptance of RepU will be driven by cost with RepU use increasing as the market price for natural uranium increases. Should MOX use be initiated in the U.S., a potential large source of RepU could be available to meet supply. As an example, approximately 0.94 kg of RepU having about 0.9 w/o ^{235}U content could be recovered from reprocessing one kilogram of current U.S. irradiated fuel. If this RepU were enriched—compensating for ^{236}U by enriching to say 5% versus about 4.2% for present-day PWR LEU fuel—with tails taken to 0.2 w/o ^{235}U, it could produce 0.15 kg of fuel worth approximately equivalent to that of PWR LEU fuel. Such a U.S. source has not been considered in any supply or cost projections to this point because reprocessing is not within current U.S. policy, and the U.S. is decades away from implementation. Reactor operation will also impact the economics as deeper burn fuels have less value relative to remaining fissile uranium content. Nonetheless, if nuclear fuel reprocessing does become a reality, primary uranium prices remain high, and suitable enrichment capacity is available, a policy of sustained single recycle of RepU could reduce domestic primary uranium demand by 15% or more.

Depleted Uranium (DU). In the enrichment process for nuclear fuel for each kilogram of enriched uranium produced, an average of 8 kg of depleted uranium (enrichment tails) is also produced. Some reenrichment of tails is being used in Russia to recover fissile uranium because a surplus of low cost enrichment capacity currently exists, but it is not a significant factor versus total world demand. In general, the existence of low cost uranium, as well as the added cost for reenrichment, results in DU not being considered to have value as a uranium supply at this time. Because stable storage of the tails is possible, emergence of lower-cost enrichment technologies could result in DU becoming a valuable energy source in the future. However, most projections take no credit for such entry into the market place. Other uses to be considered are for HEU or MOX dilution and future fast reactor core blankets. Again, such use is not expected to have any impact on market price. Most studies also assume that tails will remain at 0.3% throughout the demand period, but evolution of technology and uranium pricing could result in driving the tails to lower value trading off the additional cost of separative work units versus the cost of newly mined uranium.

Stockpiles of DU, in the form of uranium hexafluoride (UF_6), have been accumulating since the beginning of the nuclear age and the U.S. currently holds 708,189 tonnes of UF_6 in storage sites at Peducah, Kentucky and Portsmouth, Ohio. These inventories are far from homogenous and the conditions under which they would become attractive alternatives to mined natural uranium depend on many factors.

The decision of whether to mine fresh uranium, or exploit alternative sources, is largely a matter of which offers the cheaper supply. Depleted uranium stockpiles have a highly variable ^{235}U composition

(Table A1– 14) and will often require additional enrichment beyond what is needed for manufacturing LWR fuel from natural uranium. Because of this, the price of using DU will depend on the costs of enrichment, DU cylinder transport from storage to the enrichment plant, UF_6 tails storage, deconversion of UF_6 tails to U_3O_8, and its subsequent disposal.

The table shows the amount in 2006 of depleted uranium in UF_6 from in the US as a function of ^{235}U assay. The UF_6 is stored in 58890 cylinders at Paducah, Kentucky and Portsmouth, Ohio. In total there are 708,189 million tonnes of UF_6 in the U.S. One MT = 10^9 kg.

The U.S. Department of Energy currently plans to deconvert stockpiled UF_6 to U_3O_8 for stable storage until final disposal at a cost of \$2.80/kg UF_6.[f] A limited number of uses for DU exist beyond reenrichment. Depleted uranium can make an ideal matrix for down blending highly enriched uranium from dismantled nuclear weapons and its use for fast reactor blanket material has also been explored (Diehl 2004; Hertzler and Nishimoto 1994). However, with the exception of shielding applications for spent fuel storage casks, the amount of material required to meet potential needs is small compared to the current supply. This disparity is likely to grow with time, especially if demand for nuclear power increases. Alternatives for DU disposition are discussed in greater detail in Module K1.

Table A1– 14 Assay distribution of U.S. depleted uranium (DOE 2006b).

Assay Range (% ^{235}U)	No. Cylinders	MT UF_6
0.1250–0.1649	20	149
0.1650–0.2149	16,036	174,137
0.2150–0.2649	15,290	192,883
0.2650–0.3149	10,749	135,056
0.3150–0.3649	12,165	151,952
0.3650–0.4149	1,939	23,989
0.4150–0.4649	861	10,535
0.4650–0.5149	47	425
0.5150–0.5649	97	1,163
0.5650–0.6149	20	94
0.6150–0.6649	31	227
0.6650–0.7149	1,634	17,580

Reduction of Tails Assay. Although not a supply source, the DU tails assay bears mentioning as it is the sole short-term method of introducing demand elasticity available to utilities. Prior to 2000, the prevailing DU tails assay was 0.3 w/o ^{235}U. As the price of uranium has increased, the front-end cost-minimizing tails assay has decreased to perhaps 0.2 w/o ^{235}U. To place this into context, for production of 4.2% enriched fuel the reduction of tails assay from 0.3 to 0.2 w/o would decrease natural uranium requirements by 18%. Hence, its market-driven adjustment can lead to economies of primary uranium consumption similar to those listed above for the various secondary supply sources.

Recovery from Coal Ash. Coal ash, particularly ash from brown coal, can be sufficiently rich in uranium to make ash-pile stripping economically viable. This practice is not new, over three million lb U_3O_8 was recovered from ash in the U.S. through the 1970s, and uranium recovery from ash is ongoing in China. Ash piles being mined there have uranium content ranging from 20 ppm upward to 315 ppm. At 2008 prices and assuming 160 ppm uranium content, the annual ash from one medium-sized coal-fired power station would contain 100,000 pounds of U_3O_8—roughly one-eighth of the annual requirement of a 1 GWe PWR—and be worth over \$5M. With production costs estimated at \$20–35 per lb U_3O_8, it would therefore be profitable to harvest ash having U content of approximately 100 ppm or more. The size of this resource pool is unknown as a comprehensive assay of ash piles has not been conducted, but perhaps

f. Cost estimate based on communication with Uranium Disposition Services, LLC.

its greatest value is the speed with which it can be brought online if supply shock conditions were to arise. Ten to 15 years are needed for a conventional mine site to advance from discovery to production, whereas production from ash could commence in a quarter of this time (NEI 2009).

A1-6.8 Primary Supplies

Newly mined and processed uranium has been divided into four categories for purposes of world uranium supply projection by the IAEA-NEA:

1. Commonwealth of Independent States, the former Soviet Union
2. National programs
3. Chinese production
4. Market-based production.

The first three are generally perceived as captured production for "in-house" utilization and, therefore, do not have a significant impact on the world market except as avoiding import of world market-based supplies. As any of the first three categories develop cost-effective production capacity exceeding demand, they could begin to impact the market price.

Market-based production is simply the difference between the overall demand minus the secondary supplies and the first three primary supplies. As can been seen in Table A1– 15, the primary producers of uranium are Canada, Australia, Niger, Namibia, Russia and Kazakhstan. The reference data have been collected from actual bottoms-up feedback from industry along with specific country reporting of supply and demand. More recently, data have begun to be withheld as a more competitive market emerges.

Kazakhstan, a minor player in the market as recently as 2001 when it was the sixth-largest producer, is poised to overtake Australia and Canada as the world's largest yellowcake producer in 2009 or 2010. Kazakh production, mostly ISL, is expected to exceed 15,000 tU/year in 2010 and could reach 23,000 tU/year by 2015. Capacity is also set to increase in other producer nations. In Canada, where mine floods have plagued operations, production could reach 19,000 tU/year by the mid-2010s. The capacity of the Olympic Dam open pit mine in Australia, which houses the largest known uranium deposit in the world, is set to expand, but other projects there— the Jabiluka deposit, for example—are being held up by local governmental and activist resistance. Projects in the U.S. and Canada are facing similar hurdles, but new projects are moving forward in major supplier states Namibia and Russia (Steyn 2008).

Developments on the demand side have spurred growth in domestic supply with several uranium mines being reopened in the U.S. for the first time in nearly a decade. Other mine openings are being resisted by local groups; Native American tribal opposition to proposed re-openings in Arizona and New Mexico and intense local debate surrounding prospecting activities in Virginia are two examples. Regardless, U.S. mines are expected to remain a relatively minor source of uranium through the next decade.

Table A1– 15 Uranium production, tones U, 1997-2007.

Country/ Area	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007[e]
Argentina	30	7	4	0	0	0	0	0	0	0	0
Australia	5,488	4,894	5,984	7,579	7,720	6,854	7,573	8,982	9,512	7,593	7,600
Belgium	27	15	0	0	0	0	0	0	0	0	0
Brazil	0	0	0	11	56	272	230	300	110	200	340
Bulgaria	0	0	0	0	0	0	0	0	0	0	0
Canada	12,031	10,922	8,214	10,683	12,522	11,607	10,455	11,597	11,628	9,862	9,850
China	570	590	700	700	700	730	730	730	750	750	750
Czech Rep	603	610	612	507	456	465	452	412	409	375	309
France	572	452	416	296	184	18	9	6	4	3	2
Gabon	470	725	0	0	0	0	0	0	0	0	0
Germany	28	30	29	28	27	221	150	77	94	65	45
Hungary	200	10	10	10	10	10	4	4	3	2	3
India	207	207	207	207	230	230	230	230	230	230	270
Kazakhstan	1,090	1,270	1,560	1,870	2,114	2,822	3,327	3,719	4,346	5,281	7,245
Namibia	2,905	2,780	2,690	2,715	2,239	2,333	2,037	3,039	3,146	3,067	3,800
Niger	3,487	3,714	2,907	2,914	2,919	3,080	3,157	3,245	3,322	3,443	3,633
Pakistan	23	23	23	23	46	38	40	40	40	40	40
Portugal	17	19	10	14	4	0	0			0	0
Romania	107	132	89	86	85	90	90	90	90	90	90
Russia	2,580	2,530	2,610	2,760	3,090	2,850	3,073	3,280	3,275	3,190	3,381
South Africa	1,100	965	927	798	878	824	763	747	673	534	750
Spain	255	255	255	255	30	37	0	0	0	0	0
Ukraine	1,000	1,000	1,000	1,005	750	800	800	855	830	808	900
United States	2,170	1,810	1,773	1,522	1,015	902	769	878	1,171	1,805	2,000
Uzbekistan	1,764	1,926	2,159	2,028	1,945	1,859	1,603	2,087	2,300	2,260	2,300
Total	36,724	34,886	32,179	36,011	37,020	36,042	35,492	40,263	41,943	39,603	43,328

NA = not applicable

e = expected

Source: Redbooks, 1997–2007

A1-7. 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, market timing versus production of newly mined uranium, and future regulatory impacts (both positive and negative) will affect the credibility of the information. The data best represent a "speculative supply" to an uncertain demand.

The mining industry is relatively mature but will expand and utilize new techniques as dictated by ability to make profit versus a competitive market.

Most of the data used for analyses have received detailed evaluation and are as good as any speculative approach can be applying engineering judgment.

A1-8. COST SUMMARIES

This section presents low, high and nominal uranium price forecasts. Module A1, along with other front-end modules, addresses an industry with a well-developed market. Therefore, although the forecasts presented here are labeled 'costs' for consistency with the format used across this report, they should be interpreted as estimates of the long-term average uranium contract price (see discussion on the use of price data in the main body of this report).

Table A1– 16 summarizes the 100-year constant-dollar averages of the mineral index and MIT elasticity model forecasts from Section A1-2. Both models are ascribed equal credibility, so the module forecasts are generated from the average of the two. The low and high forecasts appearing in the what-it-takes table (Table A1– 17) should thus be interpreted as 95% confidence boundaries on the price forecast.

Table A1– 16 MIT and Mineral Index models: price forecasts [$/kg U] averaged over 100 years.

	Low Price (Bottom of 95% Confidence Interval)	Mean	High Price (Top of 95% Confidence Interval)
MIT Elasticity Model	88	139	227
Mineral Index Model	41	84	231
Average[1]	65	110	230
1. Rounded to the nearest $5/kgU			

Table A1– 17 "What-it-takes" (WIT) Table

Low Cost	High Cost	Nominal Cost
2012 CBR values based on second analytical method (2012$)		
$65/ kg U	**$230/ kg U**	**$110/ kg U**
2009 CBR Values based on first analytical method(2009$):		
$30/kg U	*$260/kg U*	*$75/kg U*
Composite 2012 CBR values essentially incorporating (including within assigned range) new 2012 values from additional methodology 3 rows above (2012$: no escalation assumed from 2009 values.		
$30/kgU	$260/kgU	$75/kgU
2015 CBR values based on escalation of 2012 values (whichare same as 2015 values) by 5% (2015$)		
$32/kgU	$273/kgU	$79/kgU

The approach to long term forecasting taken here explicitly avoids hypotheses over the resource discovery or technology development scenarios that give rise to the low and high outcomes. For instance, unconventional sources such as uranium in seawater, phosphate and shales may become economically attractive in the future as technologies for their recovery evolve. The 2009 CBR module discussed prospects for these technologies. But the models used in the CBR have been chosen because it is arguably not possible to develop a credible forecast of the cost of these and other commodity-specific extraction and prospecting technologies over a century-long time frame.

The actual price paid for uranium is a combination of long-term contract prices and “spot market” procurements. While spot market prices are tracked and published and in general the indicators are very close to one another, they do not necessarily indicate the appropriate price to reflect the average uranium sale on the longer-term contracts. Any slight variation of demand or supply has a significant effect on the spot price. Spot prices represent a snapshot of market conditions at the publication date when quantities traded are fairly low; inventory sales on the spot market may not reflect production cost at all. In terms of quantity, the spot market procurements only represent roughly one-tenth of the demand. The spot market can be viewed as speculative in nature and is driven by short-term impacts rather than real supply/demand interaction. Following the trends of the spot market does provide some insight into market factors as can be seen in Figure A1– 25.

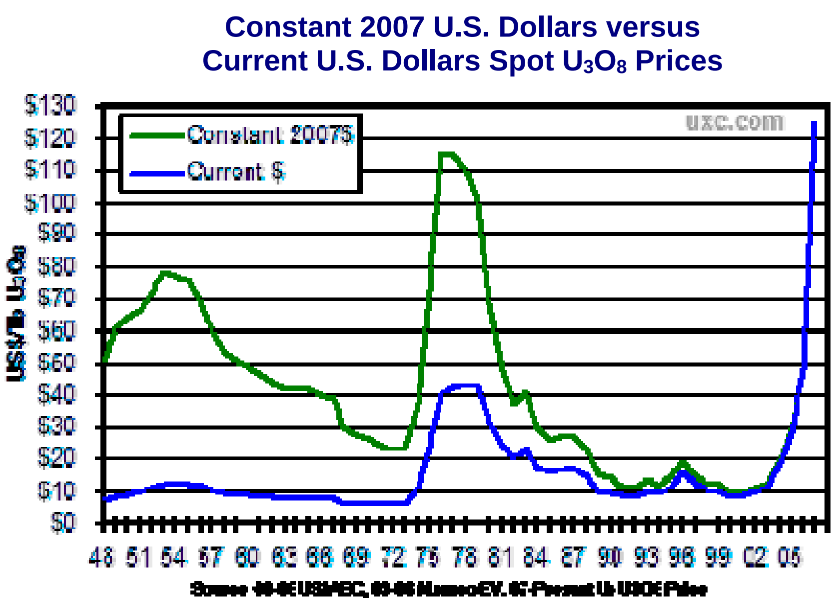

Figure A1– 25 U3O8 spot prices (UXC 2009).

The pricing in the 1990s was dominated by the influx of LEU from down-blend of Russian HEU and reduction of commercial uranium inventories. As part of the privatization of USEC in 1997, the U.S. government provided them with ~70 million pounds of yellow cake, which USEC used to ensure some return for investors. The combination of these three factors reduced the need for newly mined uranium and drove the spot market down. A flood in the largest mine in Canada, McArthur river, sparked a sharp upturn in spot market prices in 2003. The mine is now back in production, but a 2006 flood at Cigar Lake is expected to keep that Canadian mine offline until 2011–2012. Other unforeseeable events have also curtailed primary supply: a 2001 fire at Australia’s Olympic Dam mine reduced production through 2003, weather events substantially curtailed production at mines in Australia and Canada in 2006, and lower than expected ore grades affected production at McClean Lake in Canada in 2006.

Developments on the secondary side of the supply picture also contributed to the upward pressure on prices. In November of 2003, Tenex, citing unfavorable agreement terms, announced that beginning in 2004 that natural uranium from the HEU to LEU arrangement would be returned to Russia and thus would not be available for the Western market. Although this impasse was resolved and LEU deliveries were not interrupted, in 2006 the Russian government indicated that a second HEU deal would not be pursued once the current arrangement expires in 2013. This future loss of up to 9000 tU/year of supply sparked a concern about the longer-term supply of newly mined uranium to replace this important source. It is also anticipated that the significant utility and producer inventory drawdowns are complete and the market price will once again begin to respond in relation to a more stable demand including growth scenarios.

The uranium price increased more than five-fold from January 2005 to July 2007 (Figure A1– 26). Market factors combined with the supply-side effects discussed above contribute to the price increase. The relative weakness of the U.S. dollar has also affected local prices in the import-driven domestic market. Hedge funds and speculative investors since 2004 have added substantially—at least 12 million lb of U_3O_8—to the demand side of the uranium market (Steyn 2006). In addition, long-term contract volume has increased significantly from its historical average as utilities have hastened to secure supplies as hedges against further price increases. In a further hedging measure that parallels behavior during the 1970s-early 1980s price boom, utilities have also taken measures to expand their uranium stockpiles (Table A1– 18).

As of August 2009 the price of uranium has fallen to $48/lb U_3O_8 ($125/kgU), less than 40% of 2007 its peak. Although the price paid by utilities under long-term contractual agreements continues to increase, it is evident that the late price boom will be of much shorter duration than was the case in the 1970s. Moreover, a convergence of spot and contract prices is to be expected as utility shifts toward long-term contracts relieve pressure from the spot market (see discussion and data below). Figure A1– 27 compares uranium price trajectories through the two boom cycles. The greater maturity and transparency of a more mature uranium market is contributing to the present rapid stabilization in prices.

Ux U_3O_8 Prices

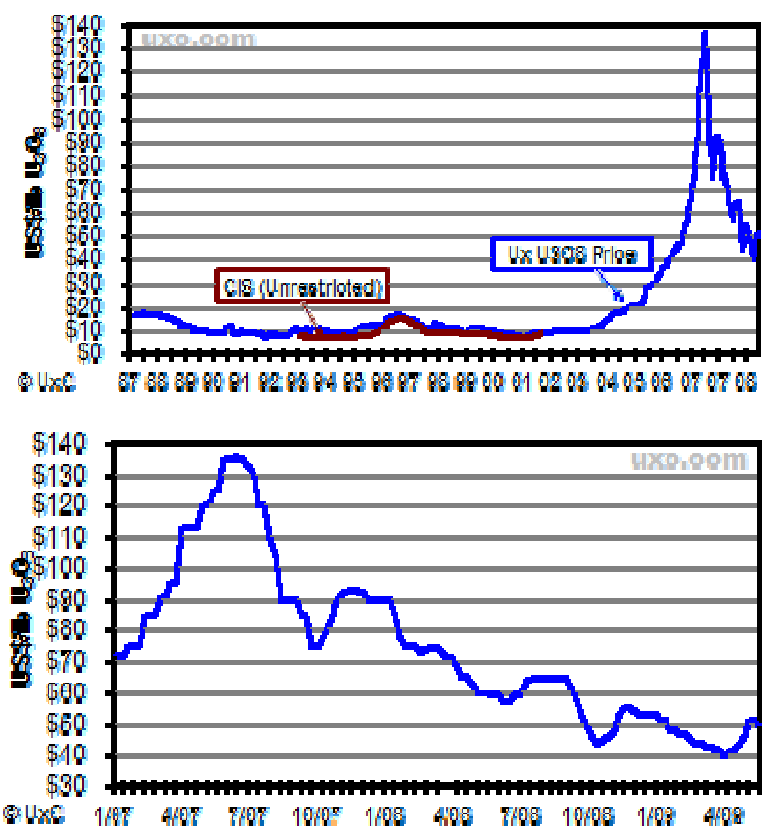

Figure A1– 26 U3O8 spot prices in current dollars, 1987–2009 (top) and January 2007–July 2009 (UXC 2009).

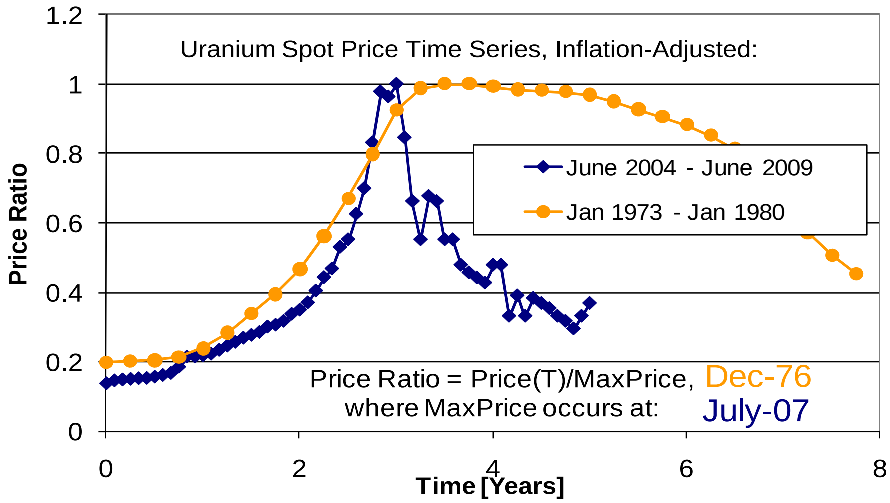

Figure A1– 27 Comparison of price histories during the late-1970s and mid-2000s booms.

Volumes of uranium contracted by utilities continued to be heavy into 2007. Table A1– 18 shows that the volume of new contracts secured by reactor owners and operators increased as the price of uranium rose and peaked. However, it is important to note that market prices, especially the spot price, do not always reflect the actual cost of uranium to utilities. While the details of contract terms are confidential, EIA data makes clear that utilities are paying considerably less for uranium than spot market prices would imply.

Table A1– 18 U.S. reactor owner and operator multi-year contract volume (thousand lb U3O8) by date of contract initiation.

Year of Contract Initiation	Minimum Volume Contracted for Delivery	Maximum Volume Contracted for Delivery
2001	49,245	76,158
2002	20,004	29,231
2003	>33,141[a]	>36,072[a]
2004	>52,038[a]	>58,207[a]
2005	>47,259[a]	>48,821[a]
2006	81,466	90,422
2007	69,565	71,078
2008	35,973	36,180

a. Some data was withheld by EIA to avoid disclosure of sensitive contractual information.
Source: US Energy Information Administration, "Uranium Industry Annual," 2001–2002, and "Uranium Marketing Annual Report," 2003–2008.

Table A1– 19 reveals that spot market volume decreased considerably in the years following 2005 as utilities exercised their rights to purchase the maximum amount of uranium they were entitled to under existing contracts. Pricing mechanisms play a role here, but even so spot market prices do affect a significant portion of uranium that is delivered under contract. For instance, Cameco reveals some information on its Web site[a] regarding pricing mechanisms utilized by its contractual agreements. Of Cameco's contracts, 60% are at least partially tied to the spot market price at delivery time, while 40% are fixed, base-escalated or negotiated annually. This figure may be changing with time, though; Table A1–19 shows that utilities have responded to higher prices by moving away from contracts that are tied to spot market prices.

a. http://www.cameco.com/

Table A1– 19 US utility annual spot and contract-specified price (dollars per lb U3O8 unadjusted for inflation) and volume (thousand lb U3O8) of delivered uranium.

	Spot Market Pricing[A]		Contract Specified Pricing	
	Volume	Price	Volume	Price
2000	16,740	8.73	28,563	12.65
2001	17,742	8.42	28,453	11.61
2002	18,591	9.57	25,063	11.15
2003	20,098	10.54	26,755	11.00
2004	14,923	13.77	37,691	12.13
2005	13,615	14.65	42,114	14.42
2006	9,523	18.04	41,164	18.18
2007	10,322	50.89	28,142	25.19
2008	10,260	64.01	31,706	37.27

a. Spot-market pricing includes contracts with pricing mechanisms tied to spot market prices at time of delivery.
Source: US Energy Information Administration, "Uranium Industry Annual," 2001–2002, and "Uranium Marketing Annual Report," 2003–2008.

It is important to differentiate short-term pressures from the longer-term picture with which this review is chiefly concerned. More recent trends anticipating a renaissance in nuclear energy have not only spurred new interests in uranium supply, but also introduced new factors into the market not seen in the recent past.

A1-8.1 Natural Uranium Production Cost and Price

The pricing market is far from disciplined or mature; companies and countries have chosen not to share any long-term contract pricing information. As a result, many of the indices stopped reporting uranium prices in 2002, and some have even withdrawn previously published data. Using published data such as spot market prices to form conclusions for the future does not appear to have a solid basis.

Estimates of future pricing often ignore uranium resource replacement via new exploration. As a result, long-term supply-demand analyses tend to have a pessimistic bias (i.e., toward scarcity and higher prices) that typically will not reflect reality. New exploration cycles may drive up uranium prices in the short term. However, this exploration should be expected to add uranium resources to the world inventory. To the extent that some of these resources may be of higher quality and involve lower operating cost than resources previously identified, this will tend to mitigate price increases. This is precisely what has happened in Canada, as the low-cost discoveries in the Athabasca Basin have displaced higher-cost production from many other regions, lowering the cost curve and contributing to lower prices. Secondary uranium supplies, to the extent that they can be considered as a very low-cost mine, have simply extended this price trend. Likewise, existing estimates generally neglect advances in extraction technologies and other factors affecting productivity per mineworker. For instance, in 1980 combined employment in the U.S., Canadian, and Australian uranium extraction industries was 26,520 persons; in 2005 employment stood at 1824 individuals (OECD 2006b). The corresponding annual production figures are 25,511 tU in 1980 and 21,615 tU in 2005. Hence, to a first approximation, productivity stood at 0.96 tU/person/year in 1980 and 11.85 tU/person/year in 2005 (Figure A1– 28). Evidently, labor inputs to uranium mining have decreased significantly.

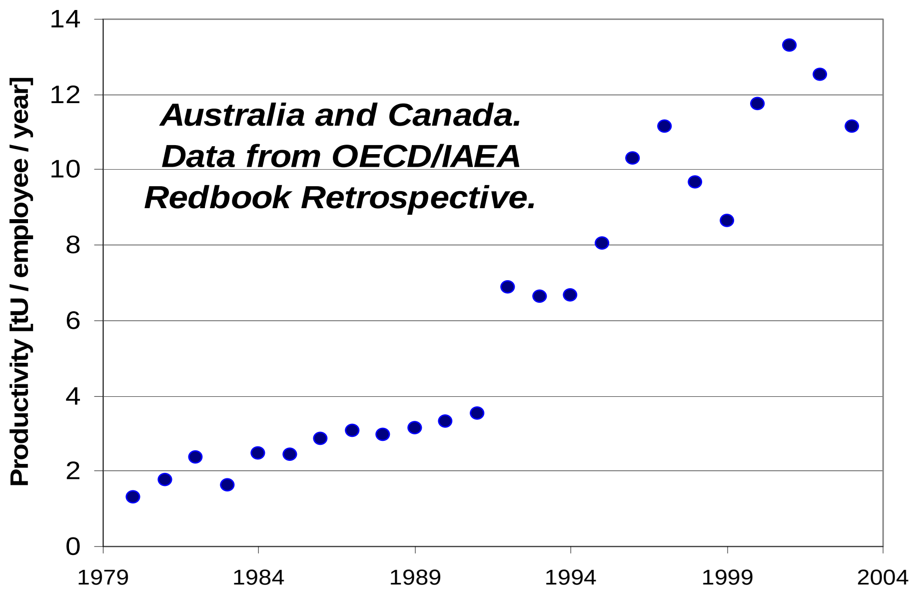

Figure A1– 28 Labor productivity, Australian and Canadian uranium mines.

The following summary reflects current information that appears valid for use in economic modeling for Advanced Fuel Cycle Initiative fuel cycle analyses.

Specific Exploration, Mining, and Milling Cost Data. The huge uranium reserves of Canada's Athabasca Basin were discovered for about U.S. $0.70/kg (2003 dollars, including unsuccessful exploration). It has been suggested that finding costs for uranium can be estimated as low as 2% of the spot price. On the high side, extrapolation of past exploration costs suggests costs as high as $1.80/kg (2005 U.S. dollars), a figure mentioned earlier in this Module. In any case, it is small fraction of the cost to produce the yellow cake product.

Supply and Demand Data. The data available through the DOE-EIA, the IAEA, and OECD/NEA have a reasonable degree of consistency relative to reserves, supply, and demand data. Most other references use that data.

Uranium Price Data. Ux Consulting and NUEXCO have Web sites that maintain "real-time" published values for spot market pricing.

Future Price Evaluation. No published sources were discovered with specific predictions of uranium prices beyond 2025. A mine-opening cycle requires around 15 years to complete; this sets the time horizon for which information available now can be used to develop production cost (and then price) estimates. Energy Resources International in 2009 forecast that the long-term (i.e., contract) uranium price would decline to less than $50/lb U_3O_8 ($130/kgU) in 2015, but rise to $67/lb U_3O_8 ($170/kgU) by 2025 (NuclearFuel 2009).

The IAEA-NEA study, *Uranium Supply to 2050,* provides the best source of speculative data relative to likely price ranges for newly produced uranium versus a broad range of demand scenarios (IEA 2001). Such data could be plotted and assumed to have linear growth to provide a speculative cost value for a dynamic model. Based on the reserves listed and the influence of secondary supplies, it would appear that uranium prices would fall well within the projections of the IAEA.

The excitement over potential growth sparked a short-term growth in the price of uranium with the spot pricing peaking at $350/kgU ($135/lb U_3O_8) in June 2007. An energetic growth in nuclear power could create a temporary lag in supply driving prices up, but that would spark more interest in supply, again bringing high prices to a reasonable market level. The reasonable market level will be influenced by policy, actual growth in nuclear power capacity, and both the timing as well as the relative cost of producing new supplies.

It is necessary to choose a distribution that can reasonably be expected to depict the likely average uranium price over the next century. Forecasts are rarely attempted over such extended periods for any mineral, and market-driven uranium price data itself has only a 40-year history. Indeed, many of the concerns discussed in preceding subsections of this report are applicable to short and medium-term prices and will have little if any bearing on long-term price trends. Nonetheless, given that uranium is a mineral with ore deposit phenomenology similar to that of other minerals and that the abundance of uranium in the earth's crust is not exceptionally low or very high as compared to other minerals of economic importance, it is reasonable to draw an analogy between the price evolutions of uranium and other minerals.

The United States Geological Survey (USGS) maintains a database (Kelly et al. 2007) of commodity prices tabulated in constant year 2005 dollars. For many minerals the data extends back to the year 1900. Many of the price histories show a gradual decline in price—regardless of the level of mining—punctuated by occasional upward and downward excursions. Some of the minerals show an upward price trend over the past century.

It is assumed that the price of uranium over the next century will continue to evolve in a manner that is not exceptional when compared to that of the USGS-tracked minerals over the past century. Therefore, to create a distribution that describes the probable average uranium price over the 21st century, the following procedure was developed.

Thirty-five minerals were selected. Those commodities in the USGS database that were omitted (peat, wood, helium, and cement) were clearly not analogous to uranium and other minerals. For each mineral, the time series data was regressed onto the function:

$P = C * e^{Mt}$

where

P = price (2005 dollars per tonne)

t = year

C and M = regression coefficients.

The data series and regression results for four minerals are depicted in Figure A1– 29. A similar analysis of historical USGS data has recently been published (Schneider and Sailor 2006).

The coefficient M is interpreted as a price growth rate with respect to time. Minerals with negative M-values have experienced declining prices; for those with positive M-values, the price has increased over the past century. Table A1– 20gives the M-values obtained for all 35 minerals. The M-coefficients for six of the minerals were positive, while 29 were negative.

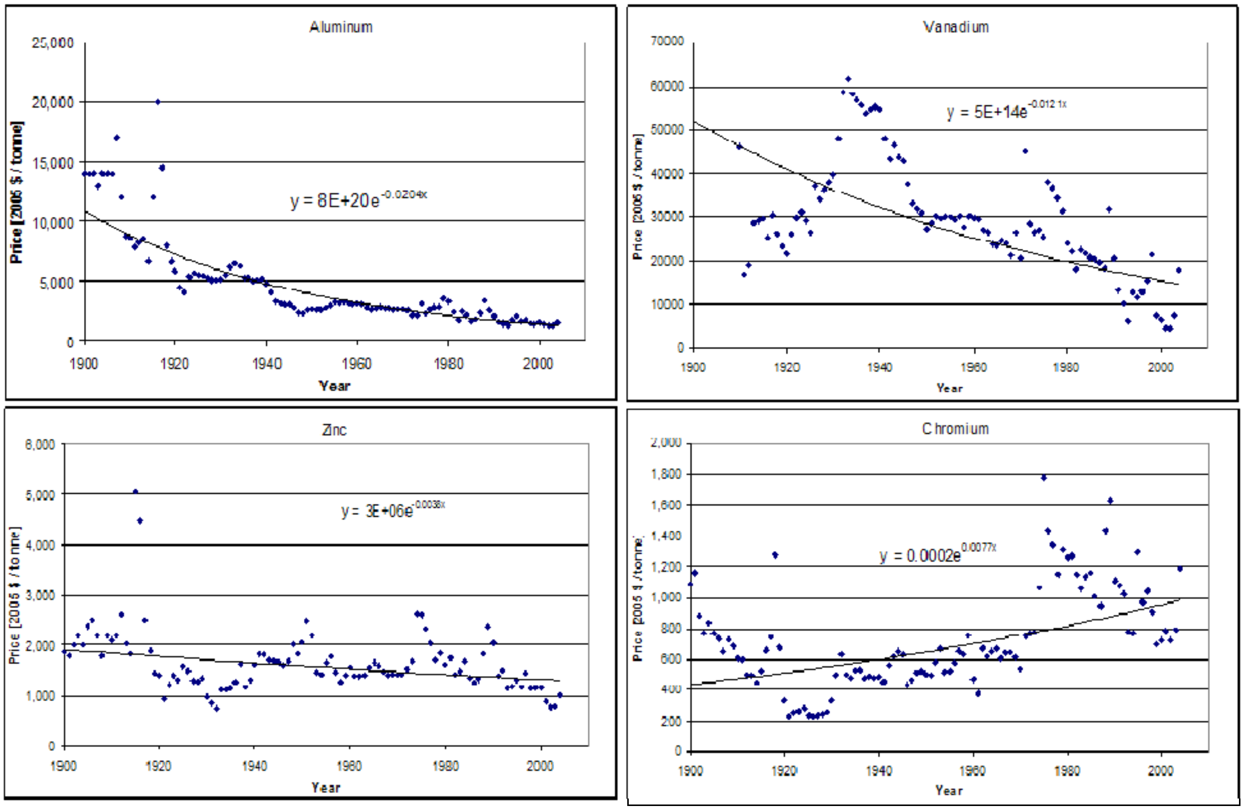

Figure A1– 29 100-year price trends for four minerals.

Table A1– 20 Regression M-coefficients for 35 minerals.

Aluminum	**Antimony**	**Arsenic**	**Bauxite**	**Beryllium**	**Bismuth**	**Boron**	**Bromine**
-0.0204	**0.0014**	**-0.0087**	**-0.0074**	**-0.0186**	**-0.0210**	**-0.0015**	**-0.0283**
Cadmium	**Chromium**	**Cobalt**	**Copper**	**Germanium**	**Gypsum**	**Indium**	**Iodine**
-0.0243	**0.0077**	**-0.0049**	**-0.0064**	**-0.0212**	**0.0041**	**-0.0407**	**-0.0153**
Iron Ore	**Lead**	**Lithium**	**Magnesium**	**Manganese**	**Mercury**	**Molybdenum**	**Nickel**
0.0029	**-0.0052**	**-0.0254**	**-0.0232**	**0.0033**	**-0.0124**	**-0.0075**	**-0.0043**
Platinum	**Pumice**	**Rhenium**	**Silver**	**Tantalum**	**Thorium**	**Tin**	**Titanium**
-0.0046	**-0.0139**	**-0.0499**	**-0.0013**	**-0.0059**	**-0.0046**	**0.0013**	**-0.0395**
Tungsten	**Vanadium**	**Zinc**					
-0.0019	**-0.0121**	**-0.0038**					

The distribution of *M*-values was then itself subjected to statistical analysis. A normal distribution was assumed and the mean and standard deviation of the distribution were calculated. Table A1-20 shows that the mean value was negative: -0.0118. This implies a decrease in average mineral prices with time.[b] The standard deviation was computed to be 0.0136, which implies about a 20% probability that the *M*-value for any given mineral will in fact be positive. The 95% confidence interval for *M*—computed by calculating the interval falling within 2 standard deviations of the mean—is thus found to be (-0.0390, +0.0153).

b. This phenomenon is well-known: witness the famous 1980 wager between the economist Julian Simon and Stanford biologist Paul Ehrlich. Simon and Ehrlich wagered $1000 against the price of a basket of five commodities chosen by Ehrlich, an early proponent of scarcity theory. Ehrlich 'bought' the basket in 1980, and Simon agreed to purchase the basket from Ehrlich in 1990 regardless of its price. The price of the basket fell considerably and Simon made a profit of $570.07 from the wager.

Table A1– 21 Statistical distribution of the 35 M-coefficients.

Most Negative	Rhenium, -0.0499
Most Positive	Chromium, 0.0077
Mean	-0.0118
Standard Deviation	0.0136
Two Standard Deviation Confidence Interval	(-0.0390, +0.0153)

Accepting that future uranium price trends should not diverge from the experience of the past century, the mean *M*-value and its confidence interval can be used to make a very approximate projection of uranium price evolution over this century. To do so, one must first select a starting point for the uranium price that roughly corresponds to a long-term average value. This was chosen to be \$120/kgU (\$46/lb U_3O_8) which corresponds closely to the historical average uranium price over the past 50 years (*viz.* Figure A1– 26). Although contract prices at the time of delivery have historically averaged somewhat less than \$100/kgU, Table A1-20 indicates that a convergence between prices paid by utilities under a variety of pricing mechanisms is taking place. Likewise, recent estimates (Lehman Brothers, Inc. 2007; UIC 2007)[c] of marginal production costs and prices indicate that \$40/lb U_3O_8 is a reasonable estimate of the equilibrium price in the medium term. Beginning from this price in 2005, then, price evolutions corresponding to the mean and upper and lower confidence interval boundary *M*-values were computed and plotted. A time-averaged uranium price for this century was computed for each of the three evolutions. The results are shown in Figure A1– 30.

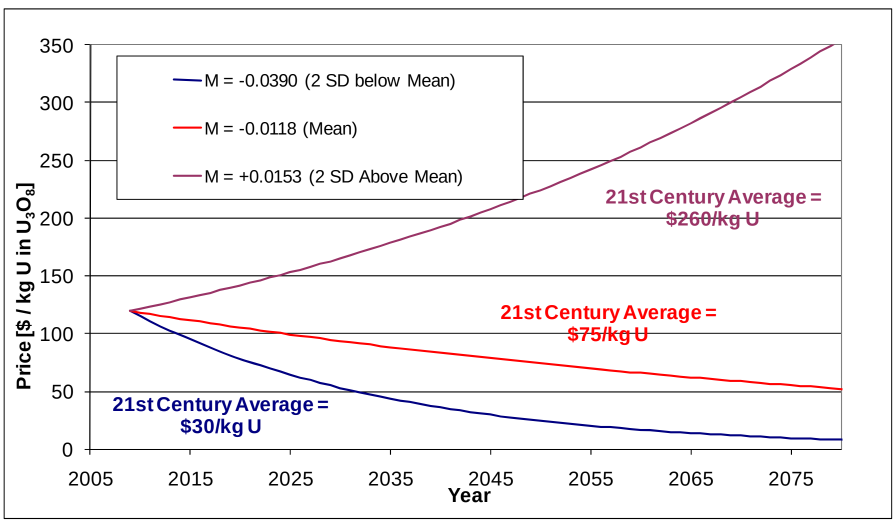

Figure A1– 30 Upper bound, most probable, and lower bound uranium price forecasts obtained from USGS data.

Therefore, a price distribution having lower, most likely, and upper values of \$25, \$60, and \$240/kgU was obtained. A logical alternate upper bound would be set by the cost of uranium extraction from seawater; however, since that cost has not been credibly estimated at less than \$300/kgU (DOE 2002), the upper bound of \$260/kgU was allowed to stand. Although the true shape of the distribution derived here is lognormal, for reasons of simplicity a triangular distribution with vertices at \$30, \$75, and \$260 is recommended.d The analysis described above accounted only indirectly for temporal variations in mining

c. This discussion, based upon a study of mine production costs conducted by International Nuclear, Inc., indicates that at production levels corresponding to expected demand in 2015, marginal production costs should be around \$20/lbU3O8.

d. It is recognized that this methodology for projecting uranium price trends differs from the approach taken in for other Modules of this document where existing literature was sufficient to formulate an estimate. To confirm that our approach is reasonable, we intensity. Another approach to describing mineral price behavior considers cumulative mining activity as an independent variable. The objective of this approach is to quantify the effect of resource depletion upon mineral prices, and applying its results to uranium price forecasting, to investigate whether the resource base can sustain a future of aggressive nuclear growth.

A rapid increase in mining activity would be expected to lead to price increases, and minerals with accelerating mining rates would tend to rise in price when compared to minerals with stagnant or declining mining rates. One approach to addressing these questions would be to compare a time period in which mining activity increased rapidly to one that is less active. The USGS data (Kelly 2007) shows that across the full spectrum of minerals mining activity accelerated rapidly between 1947 and 1974, less rapidly after 1974. Mineral prices fell over both time periods, but not as rapidly between 1947 and 1974 as after 1974.

Table A1– 22 shows the effect of resource depletion rate on price gleaned from analysis of the USGS time series data. Over the 1974–2004 period, the minerals were extracted at an average rate 1.65 times larger than in 1974. Regression analysis showed that the M-coefficent for this time period was larger in absolute value than for the full data series presented above. Therefore, prices declined more rapidly between 1974 and 2004 than was the case for the full century-long period studied earlier. If the period of analysis is 1947–1977, Table A1– 22 shows that extraction rates increased rapidly in the post-1947 period. Therefore mineral prices would be expected to decline less rapidly and this is indeed the case: the price of the basket of minerals was almost unchanged over the 1947–1977 period (Schneider and Shah 2008).

To place the M-coefficients of Table A1– 22 into context, they may be employed as described above to project average uranium prices over this century. If uranium consumption followed the low-growth trajectory represented by the 1974–2004 data (M = -0.0335), its price would average about $40/kg, while if it were extracted much more rapidly (following the 1947–1977 trend with M = -0.0002 its price would remain near the present-day assumed marginal production cost value of $120/kg.

Table A1– 22 M-coefficients for USGS minerals, 1974–2004 and 1947–1977.

Time Period	1974–2004	1947–1977
Number of Minerals in Sample	34	27
Mining Rate Acceleration Metric[a]	1.65	3.16
Average M-value	-0.0335	-0.0002
a. Defined as the average annual mining rate over the full time period divided by the amount mined in the first year of the time period. Thus, it is a measure of the average rate at which the mineral is being extracted.		

Similarities and differences between uranium and many other minerals may be briefly summarized. Uranium is uncommon in the Earth's crust, its ores must be reasonably well-concentrated to be economically viable, at current consumption rates, the earth hold a few decades of confirmed-plus-estimated uranium reserves, it has no natural substitutes, and demand for it is not diversified. These factors may make uranium an "exceptional" mineral, one that would not be expected to obey the trends presented so far. If that is the case, some minerals offer better analogies to uranium than others, or the listed explanatory variables may not even be significant drivers of price trends.

As mentioned above, the overall abundance of uranium is middling in comparison to that of other minerals. Certain types of uranium are also abundant in minerals like silver, copper, gold, and iron, making co-extraction of these minerals worthwhile. Examples include hematite-granite complex deposits such as Olympic Dam, uranium-vanadium deposits such as found on the Colorado Plateau, and solution breccia pipe-type deposits, which can additionally contain economically viable zinc and lead sulfides. The in-situ leaching technique, predominantly used for the extraction of uranium from sandstone roll-front

have undertaken a peer review process that includes a consultation with fuel cycle experts at the Nuclear Energy Institute and publication and presentation in professional society venues. Regardless, given a system as complex as the uranium market we recognize the impossibility of true high-fidelity forecasting of long-term behavior.

deposits, has thus far played a considerably more significant role in the uranium extraction industry than for most other minerals. It has grown to account for about 20% of world uranium production and 80% in the U.S. but is not used at all for the vast majority of minerals depicted in Table A1– 23. Most uranium mining is still carried out using open-pit and underground approaches; however, so advances in these areas would continue to benefit the uranium industry as well as the broader mining sector.

Laving in-situ leaching aside, the concentration factor at which uranium extraction is economically feasible is consistent with that of other minerals. The concentration factor is defined as the ore grade of an economically viable deposit divided by the average grade in the earth's crust. For uranium, taking 1000 ppm to be a viable concentration, the concentration factor is (1000/2.8) = 180. Other common minerals have concentration factor thresholds bracketing this value: gold, 2,500; iron, 10; mercury, 10,000; lead, 2,500; copper, 100 (Griffits 1973).

(Schneider, Shah 2008) collected data for each USGS mineral for five explanatory variables:

- Crustal abundances
- Concentration factors
- Years of known reserves
- Demand diversification
- Existence of substitutes.

To explore the dependence of price upon variations in these supply and demand side drivers, the minerals were binned into categories according to their properties in each category relative to uranium and the M-value distributions of the minerals in each bin were calculated. The distributions were subjected to statistical analyses to explore their significance as explanatory variables with results shown in Table A1– 23 through Table A1– 27.

Table A1– 23 Mineral crustal abundance relative to uranium and its effect on price trends.

Mineral	Abundance [ppm]	Mineral	Abundance [ppm]	Mineral	Abundance [ppm]
More Than One Order of Magnitude Less than that of Uranium		***Within One Order of Magnitude of Uranium***		***More Than One Order of Magnitude Greater than Uranium***	
Rhenium	0.0004	Iodine	0.5	Copper	55
Platinum	0.005	Germanium	1.5	Zinc	70
Mercury	0.08	Molybdenum	1.5	Nickel	75
Silver	0.08	Tungsten	1.5	Chromium	100
Bismuth	0.17	Arsenic	1.8	Vanadium	135
Antimony	0.2	Tin	2	Titanium	570
Cadmium	0.2	Tantalum	2.4	Manganese	950
Indium	0.2	Bromine	2.5	Magnesium	23000
		Beryllium	2.8	Iron Ore	56000
		Uranium	**2.8**	Aluminum	82000
		Thorium	9.6		
		Boron	10		
		Lead	12.5		
		Gallium	15		
		Lithium	20		
		Cobalt	25		
M-Value	***Std Dev***	***M-Value***	***Std Dev***	***M-Value***	***Std Dev***
-0.019	**0.019**	**-0.015**	**0.021**	**-0.010**	**0.015**

Table A1– 24 Mineral concentration factor relative to uranium and its effect on price trends.

Mineral	Concentration Factor	Mineral	Concentration Factor	Mineral	Concentration Factor
More Than One Order of Magnitude Less than that of Uranium		***Within One Order of Magnitude of Uranium***		***More Than One Order of Magnitude Greater than Uranium***	
Bismuth	1.5	Titanium	62	Silver	3750
Aluminum	4	Cobalt	80	Tungsten	4000
Antimony	5	Copper	150	Beryllium	4000
Iron Ore	9	Nickel	175	Chromium	4500
		Manganese	190	Mercury	100000
		Lithium	240		
		Uranium	**350**		
		Zinc	370		
		Molybdenum	770		
		Platinum	1000		
		Tin	2500		
		Lead	3300		
M-Value	***Std Dev***	***M-Value***	***Std Dev***	***M-Value***	***Std Dev***
-0.009	**0.013**	**-0.009**	**0.013**	**-0.005**	**0.010**

Table A1– 25 Years of reserves relative to uranium and its effect on price trends.

Mineral	Reserves / Annual Production	Mineral	Reserves / Annual Production	Mineral	Reserves / Annual Production
At Least 50% Less than that of Uranium		***Within +/- 50% of Uranium***		***At Least 50% Greater than Uranium***	
Indium	6	Thallium	38	Cobalt	122
Antimony	13	Tungsten	40	Titanium	122
Silver	14	Manganese	40	Bauxite	141
Lead	20	Nickel	41	Lithium	195
Arsenic	20	Iron Ore	47	Vanadium	208
Zinc	22	Rhenium	56	Platinum	318
Tin	22	Bismuth	57	Molybdenum	480
Cadmium	26	**Uranium**	**76**	Iodine	593
Copper	31			Beryllium	630
Mercury	33			Bromine	Large
Tantalum	33			Gypsum	Large
Boron	36				
M-Value	***Std Dev***	***M-Value***	***Std Dev***	***M-Value***	***Std Dev***
-0.009	**0.012**	**-0.006**	**0.025**	**-0.015**	**0.013**

Table A1– 26 Demand diversification and its effect on price trends.

	Diversified (No industry accounts for more than 75% of consumption)		**Not Diversified** (One industry accounts for more than 75% of consumption)	
Number of Minerals	**15**		**10 (+ uranium)**	
	M-Value	Std. Dev.	M-Value	Std. Dev.
	-0.010	0.010	-0.021	0.025

Table A1– 27 Existence of substitutes and its effect on price trends.

	One or more substitutes evident		No substitutes, or substitutes listed as inferior	
Number of Minerals	**20**		**11 (+ uranium)**	
	M-Value	Std. Dev.	M-Value	Std. Dev.
	-0.013	0.013	-0.005	0.020

The M-value distributions of the mineral populations in each category for every explanatory variable were tested for statistically significant differences in their variances and means. It was found that with 90% confidence the means of all distributions were indistinguishable. Therefore, the study concluded that variations in Crustal Abundance, Concentration Factor, Years of Known Reserves, Demand Diversification and Existence of Substitutes do not lead to demonstrably dissimilar mineral price trajectories, although differences in variances were in some cases significant (Schneider, Shah 2008).

The discussion has thus far focused upon uranium in analogy to other minerals. It is useful to close with a comparison of uranium price trends to those of fossil fuels. While uranium is geologically dissimilar from these commodities, they share the role of producing a singular end-use product. Uranium and fossil fuel prices have to an extent moved in sympathy (Figure A1– 31), experiencing booms in the 1970s to early1980s and again more recently (note that many mineral commodities also went through price booms in the 1970s–1980s; see Figure A1– 31). Inelastic demand has caused upward pressure on oil and gas prices. Uranium demand is also inelastic: with short of alterations in the fuel cycle that require decades to achieve, only limited steps can be taken in the short run to reduce uranium requirements. This landscape tight supply and inflexible demand would give rise to the downside (high cost) uranium price scenario presented in this module, where the mid-century average production cost (and hence equilibrium price) of the resource has more than doubled from 2009 values.

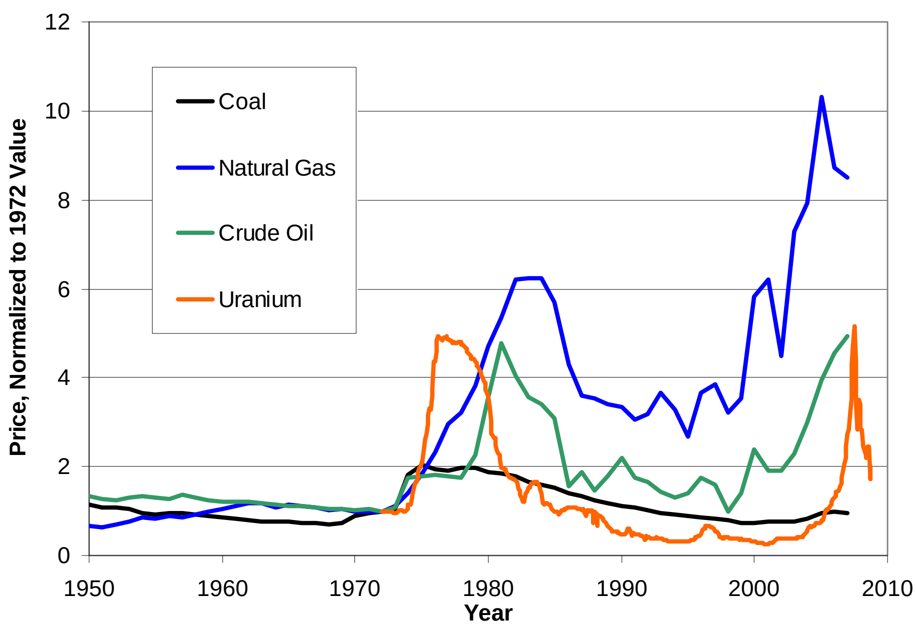

Figure A1– 31 Inflation-adjusted uranium and fossil fuel prices, 1972–2008. 1972 price = 1.

The module cost information is summarized in the What-It-Takes (WIT) cost summary in Table A1– 28. 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 A1– 32. Note that the mean cost associated with this skewed distribution is $122/kgU. See Section A-6.1 for explanation.

Table A1– 28 Cost summary table, 2009$

What-It-Takes (WIT) Table				
Reference Cost(s) Based on Reference Capacity	Reference Cost Contingency (+/- %)	Low Cost	High Cost	Nominal Cost
$50–300/kgU	NA	$30/kgU	$260/kgU[e]	$75/kgU
Reflects near-term (next 10–15 years)				

Since the above costs represent long term prices rather than spot market projections, the issue of cost escalation arises. Long term stable prices must have underlying costs, which are subject to long term escalation. For this reason the costs in Table A1– 28 are escalated to 2017$ by 14% in Table A1–29 below. Table A1–30 summarizes all unit costs from four versions of the AFCBD: 2009, 2012, 2015, and 2017.

Table A1–29 Cost summary table escalated to 2017$.

What-It-Takes (WIT) Table					
Reference Cost(s) Based on Reference Capacity	Reference Cost Contingency (+/- %)	Low Cost	Mode Cost	Mean Cost	High Cost
$50–300/kgU	NA	$34/kgU	$86/kgU	$139/kgU	$296/kgU[f]
Reflects near-term (next 10–15 years)					

Table A1–30 Cost summaries by AFC-CBD editions

AFC-CBR Year (also base yr for constant $ costing)	Low	Mode	High	Mean	Change Basis from previous AFC-CBD
2009	30	75	260	122	New analysis by Module A author
2012	65	110	230	135	Supplemental analysis by Module A author essentially supporting original 2009 analysis by being included within 2009 range
2015	32	79	273	128	2009 range selected as basis since it is more inclusive and incorporates 2012 range. Escalation of 2009 values by 5%
2017	34	86	296	139	Escalation of 2009 values by 14%

e. The authors recognize that uranium and enrichment spot prices have recently exceeded the high-cost range provided in this cost basis. These price trends continue to be evaluated and the cost ranges in the report may continue to be revised as appropriate in future updates. The cost basis reflects reasonable expectations about uranium and enrichment long-term contract prices applicable to reactors with long operating lives, rather than reflecting market spikes as experienced in the 1970s and observed in the spot market U_3O_8 prices circa 2007.

f. The authors recognize that uranium and enrichment spot prices have recently exceeded the high-cost range provided in this cost basis. These price trends continue to be evaluated and the cost ranges in the report may continue to be revised as appropriate in future updates. The cost basis reflects reasonable expectations about uranium and enrichment long-term contract prices applicable to reactors with long operating lives, rather than reflecting market spikes as experienced in the 1970s and observed in the spot market U_3O_8 prices circa 2007.

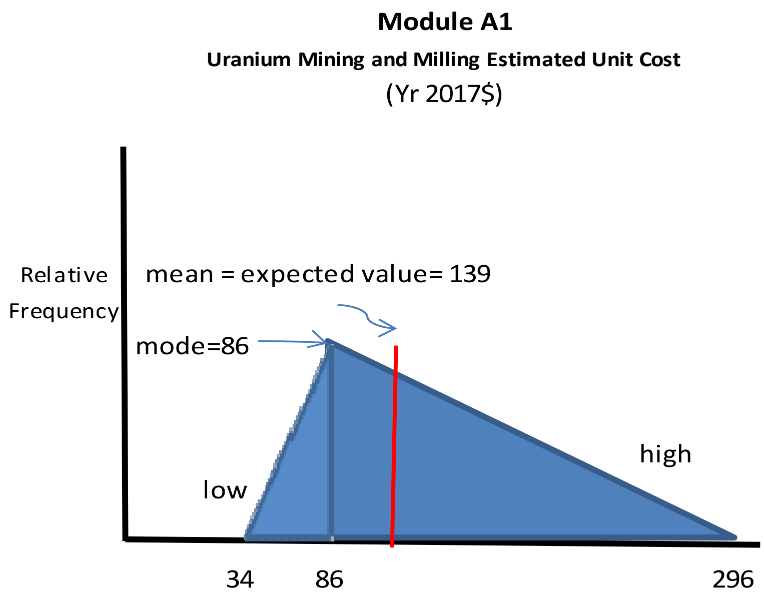

Figure A1– 32 Uranium mining & milling estimated cost frequency distribution.

A1-9. SENSITIVITY AND UNCERTAINTY ANALYSIS

Uranium Cost Sensitivity. The cost of uranium represents about 20% of the cost of fuel. A doubling of the ore price has little sensitivity in terms of the total fuel cycle cost. The sensitivity from a $150/kgU increase in price is in the range of ~1 mil/kWh relative to the cost of electricity.

Implication of expanding use of secondary sources of uranium and growth in price of natural uranium can become the driver for enhancements and capacity growth for new enrichment technologies and consideration for expanded use of existing tails and reprocessed uranium. With laser enrichment, or if the present high prices are sustained, even depleted uranium could be considered for cost-effective supply.

A1-10. REFERENCES

Cameco 2016 – "Uranium Price Sensitivity," https://www.cameco.com/invest/markets/uranium-price-sensitivity Cochran, R. and N. Tsoulfanidis, 1999, *The Nuclear Fuel Cycle: Analysis and Management*, 2nd Edition, American Nuclear Society, 1999.

Chapman, P.F., 1975, Energy analysis of nuclear power stations, *Energy Policy*, 3(4), 285-298.

Cochran R.G., Tsoulfanidis N., *The Nuclear Fuel Cycle: Analysis and Management,* American Nuclear Society, 1999 (book)

Deffeyes, K. S. and I. D. MacGregor, 1980, "World Uranium Resources," *Scientific American*, 242, 66–76, January 1980.

Diehl, P., 2004, *Re-enrichment of West European depleted urnanium tails in Russia. WISE Uranium Project*, 2004.

Diehl, Peter and Am Schwedenteich, 2005, World Information Service on Energy, Uranium Project Web Site general information, www.wise-uranium.org, December 22, 2005, Web page accessed August 20, 2009.

DOE, Energy Information Administration, 2008, *Uranium Industry Annual—2008*, Office of Coal, Nuclear, Electric and Alternate Fuels, U.S. Department of Energy, http://www.eia.doe.gov/fuelnuclear.htm, Web page accessed August 20, 2009.

DOE, 2006a, "Proposed Long-Term Uranium Sales Strategy," DOE Offices of Nuclear Energy, Environmental Management and Defense Nuclear Nonproliferation, http://www.ne.doe.gov/pdfFiles/proposedDoeLtUraniumSalesStrategyIndustryPresentationAug%204th2006.pdf, August 4, 2006, Web page accessed August 20, 2009.

DOE, 2008a, "Excess Uranium Inventory Management Plan," DOE Office of Nuclear Energy, http://www.ne.doe.gov/pdfFiles/inventory_plan_unclassified.pdf, December 16, 2008, Web page accessed August 15, 2009.

Energy Watch Group, 2006, "Uranium Resources and Nuclear Energy," http://www.lbst.de/ressources/docs2006/EWG-paper_1-06_Uranium-Resources-Nuclear-Energy_03DEC2006.pdf, December 2006, Web page accessed August 21, 2009.

Environmental Protection Agency, 1995, "Extraction and Benefication of Ores and Minerals: Volume 5, Uranium," EPA 530-R-94-032, 1995.

Financial Review 2016 – "Uranium spot prices descend beyond decade low," Financial Review, July 5, 2016, http://www.afr.com/business/mining/uranium/uranium-spot-prices-descend-beyond-decade-low-20160705-gpyupv

Global InfoMine, Inc., 2005, "Olympic Dam MineSite Feature," http://olympicdam.infomine.com, November 15, 2005, Web page accessed April 29, 2007.

Griffits, W. R., 1973, U.S. Geological Survey Professional Paper 820, 1973.

Hertzler, T. J. and D. D. Nishimoto, 1994, *Depleted Uranium Management Alternatives*. Idaho National Engineering Laboratory, Idaho Falls, ID. EGG-MS-11416, 1994.

IAEA. 2001. Analysis of Uranium Supply to 2050. Vienna: International Atomic Energy Agency.

IMF, 2017, Primary Commodity Prices. Prices & Forecasts, Monthly Data. International Monetary Fund.

International Energy Agency, 2001, *Analysis of Uranium Supply to 2050*, http://www-pub.iaea.org/MTCD/publications/PDF/Pub1104_scr.pdf, Web page accessed August 20, 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/, 2007, Web page accessed August 20, 2009.

Lehman Brothers, Inc., 2007, “Uranium Price Outlook,” 2007 Edition, cited in *Nuclear Fuel Cycle Monitor*, June 2007.

Nuclear Engineering International (NEI), 2009, “Turning Ash into Cash,” April 2009.

NuclearFuel, 2009, “Spot price of U_3O_8 moves up to over $51/lb,” June 15, 2009.

OECD Nuclear Energy Agency, 2006a, *Uranium 2005: Resources, Production and Demand* (also known as *The Red Book*), OECD/NEA-IAEA: Paris 2006.

OECD Nuclear Energy Agency, 2006b, *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*, OECD/NEA-IAEA: Paris 2008.

OECD-NEA & IAEA. 2010. Uranium 2009: Resources, Production and Demand: Jointly published by OECD Nuclear Energy Agency and International Atomic Energy Agency.

Palisade 2016, @Risk, Palisades Corporation.

Prasser, H-M., et al., 2008, “Sustainability of Uranium Sources,” in Proc. PHYSOR 2008, Interlaken, Switzerland, September 2008.

Pool, T., 2006, *2005 Global Uranium Symposium*, in Steyn, 2006.

Schneider, E. A., 2005, “A Survey of Uranium Supply Curve Estimates,” in *Trans. Am. Nucl. Soc.,* **92**, San Diego, CA, June 2005.

Schneider, E. and N. Shah, 2008, “Near Term Deployment, Long Term Impact: Uranium Price Over the Lifetime of New Capacity,” in *Proc. ICONE 2008*, Orlando, FL, May 2008.

Schneider, E., and Sailor, W. C., 2006. Nuclear Fission. Science & Global Security, 14(2-3), 183-211.

Steyn, J., 2008, “Mining the Supply Gap,” *Nuclear Engineering International*, September 2008.

Smith, P. and J. Storm van Leeuwen, , 2005, “Nuclear Power: the Energy Balance, Chapter 2: From Ore to Electricity Production and Uranium Resources,” http://www.stormsmith.nl/report20050803/Chap_2.pdf, July 2005, Web page accessed August 21, 2009.

The Ux Consulting Company, LLC, 2009, http://www.uxc.com, Web page accessed August 20, 2009.

Uranium Information Centre, 2007, “Uranium Markets,” Nuclear Issues Briefing Paper 36, March 2007.

Uranium Information Centre, 2005, “Supply of Uranium,” Nuclear Issues Briefing Paper #75, 2005.

Wise Uranium Project, 2008, “Recovery of Uranium from Phosphates,” http://www.wise-uranium.org/purec.html, Web page accessed August 20, 2009.

World Nuclear Association, Information, and Issue Brief, 2009, “Supply of Uranium,” August 2009, www.world-nuclear.org/info/inf75.htm, Web page accessed August 30, 2009.

A1-11. BIBLIOGRAPHY

Deutch, J., Moniz, E. et al., "The Future of Nuclear Power: an Interdisciplinary MIT Study," technical report, 2011. Webpage accessed July 13, 2012: http://web.mit.edu/nuclearpower/. Refer to Chapter 3 Appendix – Uranium Resource Model. (MIT 2011)

DOE, 2002, "Generation IV Roadmap: Report of the Fuel Cycle Crosscut Group," U.S. DOE Report, March 2002.

OECD Nuclear Energy Agency and International Atomic Energy Agency, "Uranium 2011: Resources, Production and Demand," technical report NEA 7059, OECD Paris, 2012.

"Projections to 2030," in *Nuclear Engineering International* special issue *World Nuclear Industry Handbook 2012*, June 2012. (http://www.neimagazine.com/journals/Power/NEI/June_2012/attachments/020neihbk2012_z.pdf

Roskill 1991, The Economics of Uranium, 3rd Ed., Roskill Information Services, London, England.

Steyn, J., 2006, "Will Supply Suffice?" *Nuclear Engineering International*, September 2006.

US Geological Survey, "Data Series 140: Historical Statistics for Mineral and Material Commodities in the United States," webpage accessed August 12, 2012: http://minerals.usgs.gov/ds/2005/140/

World Nuclear Association, "Information Brief 23: World Uranium Mining," August 2012. http://www.world-nuclear.org/info/inf23.html (WNA 2012)

Module A2

Thorium Mining and Milling

Module A2

Thorium Mining and Milling

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

- **Constant $ base year for 2017 Update:** FY 2017
- **Nature of this 2017 Module update from previous AFC-CBRs:** Escalation only from 2009
- **Estimating Methodology for latest technical update (2009) from which this 2017 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 basicaly 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

A2-RH REVISION HISTORY

- **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.
- **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$)
- **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.

A2-1 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:

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

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

A2-2 FUNCTIONAL AND OPERATIONAL DESCRIPTION

A2-2.1 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 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

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).

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.

A2-2.2 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.

A2-3 PICTURES AND DIAGRAMS

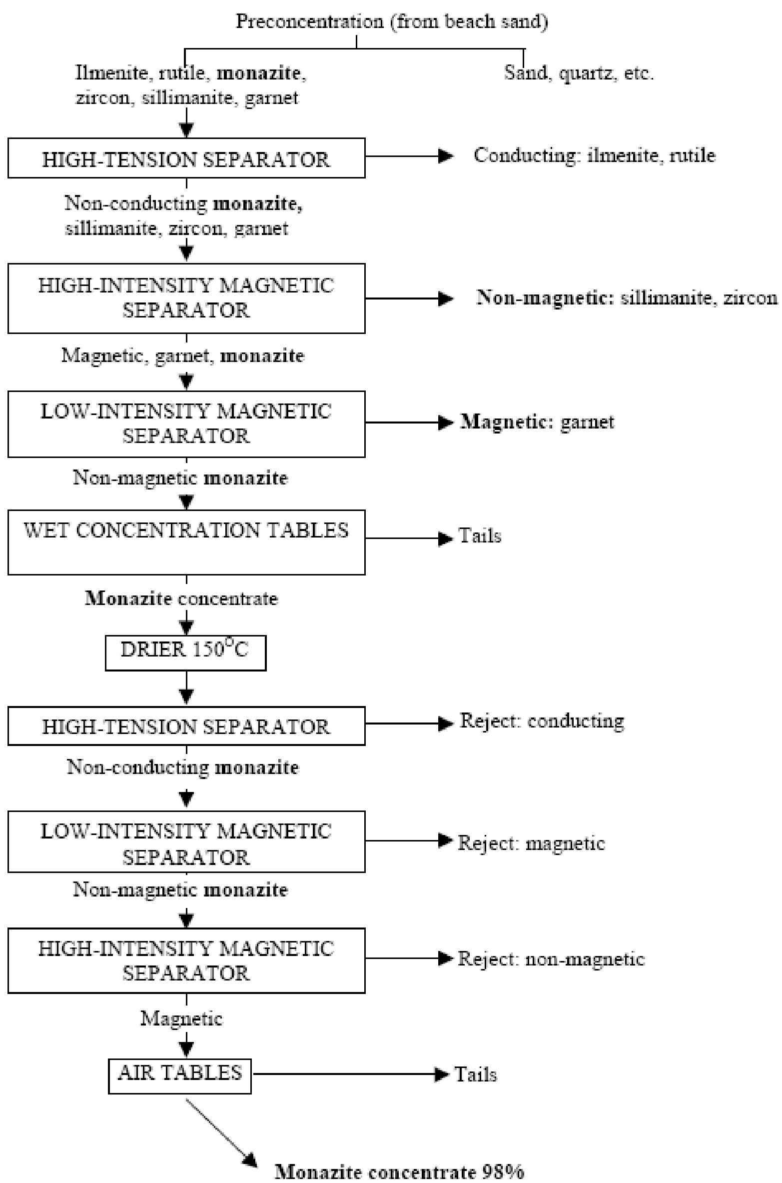

Figure A2-1. Flowsheet for monazite isolation (IAEA 2005).

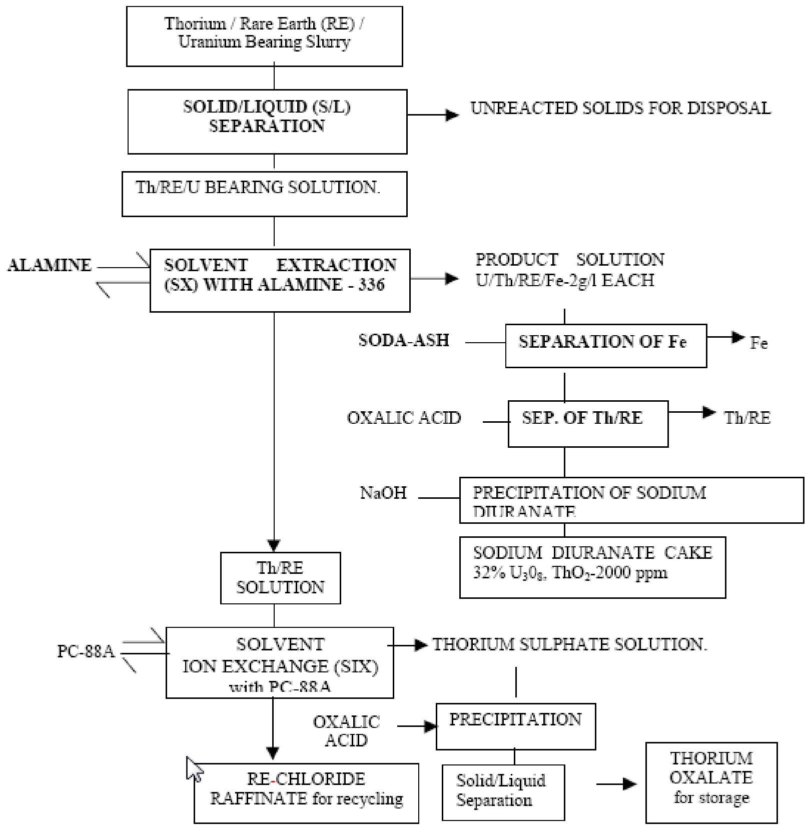

Figure A2-2. Flowsheet for thorium oxalate production from monazite (IAEA 2005).

A2-4 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.

A2-5 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.

A2-6 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.

A2-6.1 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.

A2-6.2 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).

A2-6.3 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

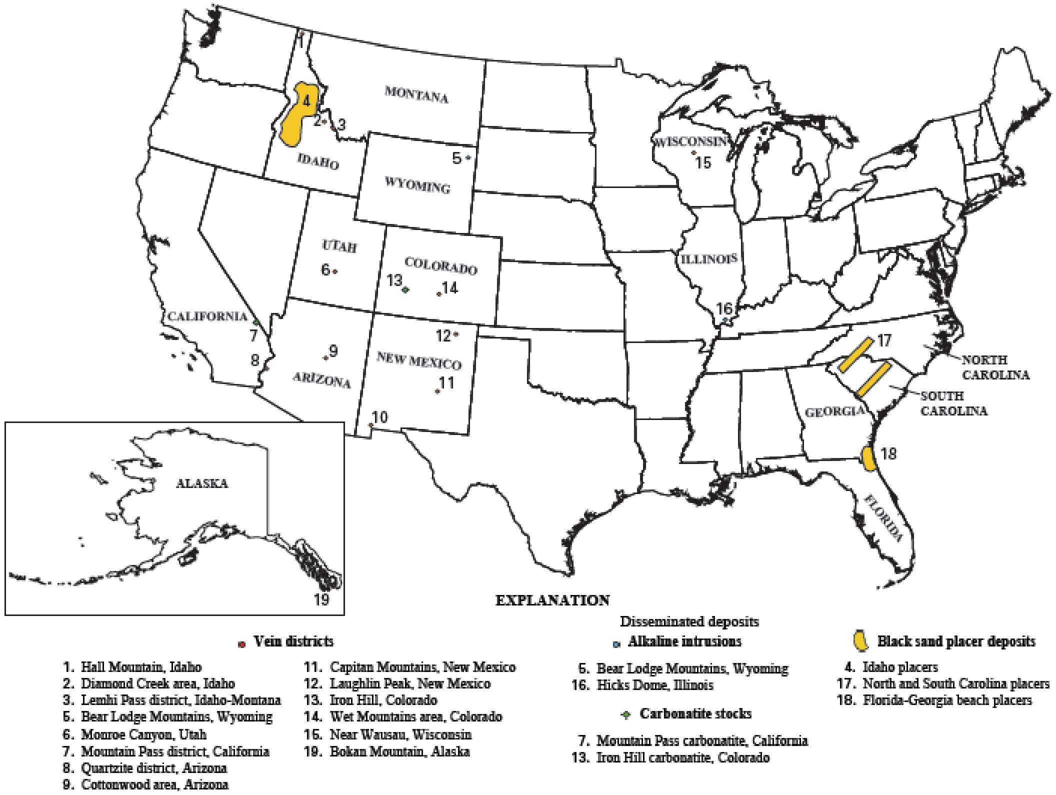

Figure A2-3. Location of prospected thorium deposits in the United States (Van Gosen et al, 2009).

A2-6.4 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.

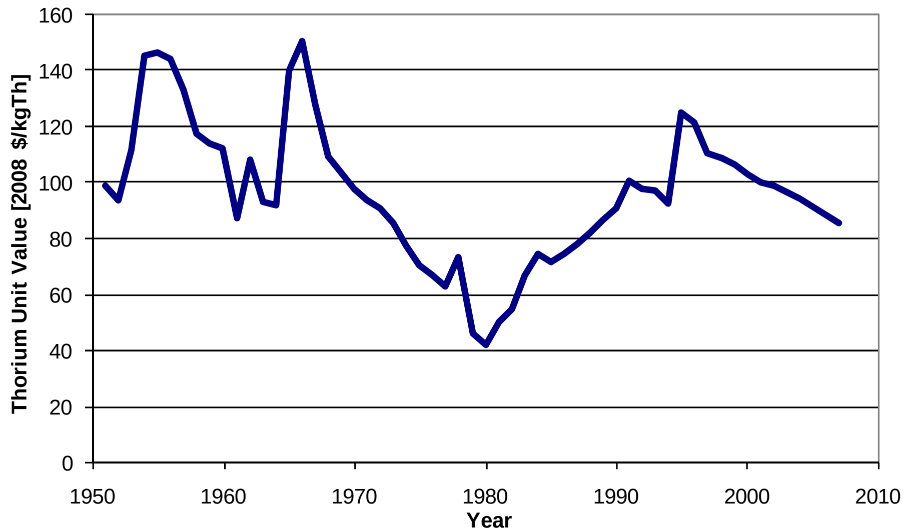

Figure A2-4. Thorium unit value, world mass-weighted average, 1952 to present, data in 1998 U.S. dollars (Hedrick 2009).

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.

A2-6.5 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.

A2-6.6 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).

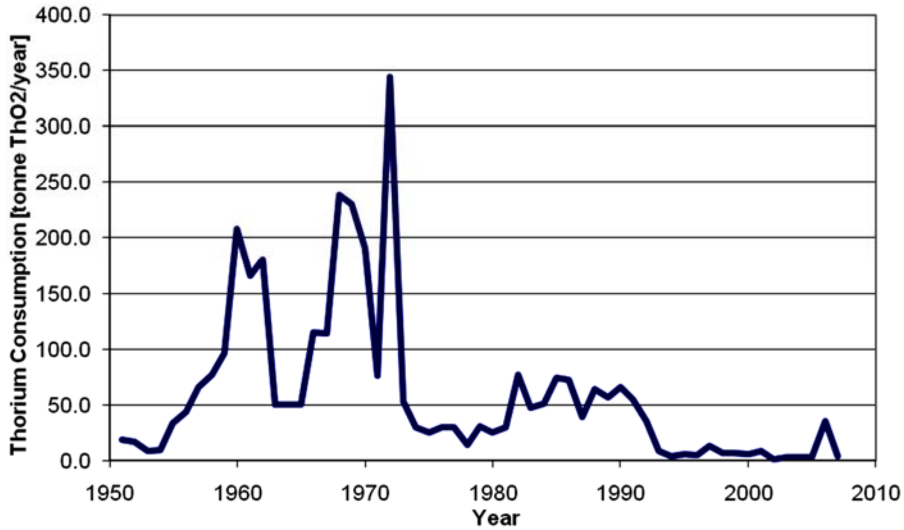

Figure A2-5. World thorium consumption, 1952 to present (Hedrick 2009).

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 2005). 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.

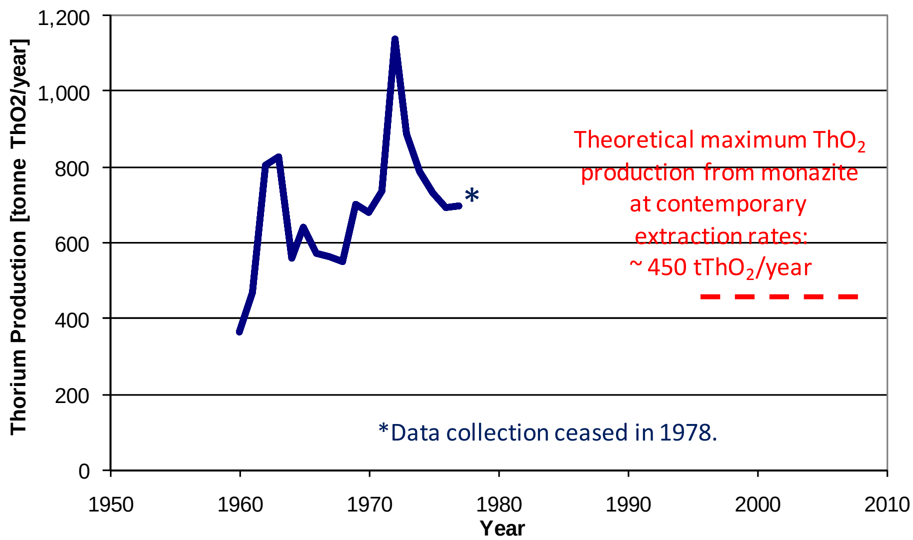

Figure A2-6. World primary thorium production (Hedrick 2000).

A2-7 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.**

A2-8 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 A2-12 gives the WIT values for the 2017 update]

Low Cost	High Cost	Nominal 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.

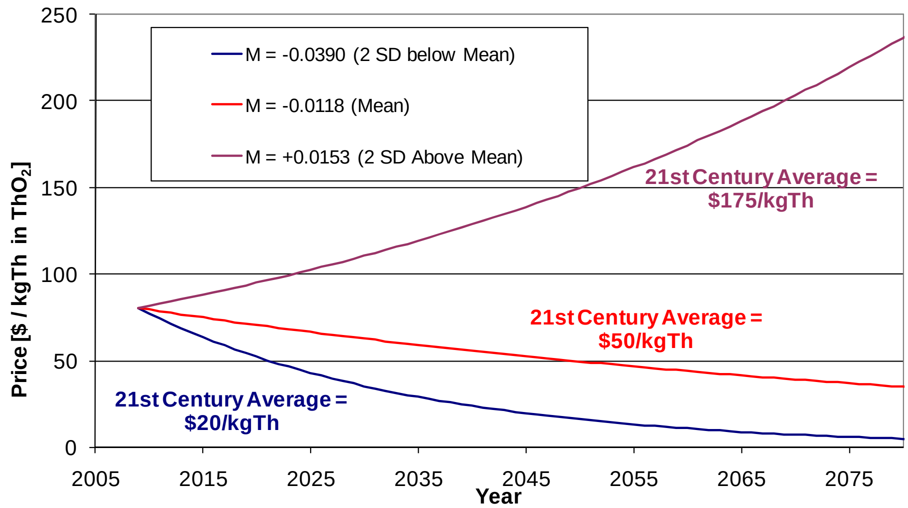

Figure A2-7. Upper bound (purple), most probable (red), and lower bound (blue) uranium price forecasts obtained from USGS mineral price model data.

A2-8.1 Thorium Production Cost and Price

The module cost information is summarized in the What-It-Takes (WIT) cost summary in Table A-10. 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 A2-10. 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	Nominal 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 A2-11 below shows the year 2015 $ costs.

Table A2-11. 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 A2-12. Cost summary table escalated to 2017 $. [Note: factor of 1.14 esed 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
$84/kgTh	NA	$23/kgTh	$57/kgTh	$93/kgTh	$200/kgTh
For Th as ThO_2 (99.9% purity)					

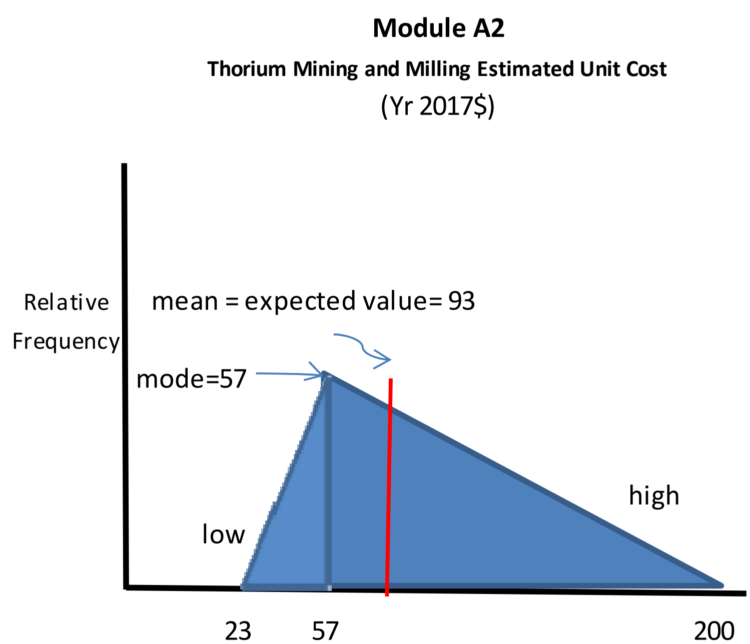

Figure A2-8. Thorium mining and milling estimated cost frequency distribution

A2-9 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.

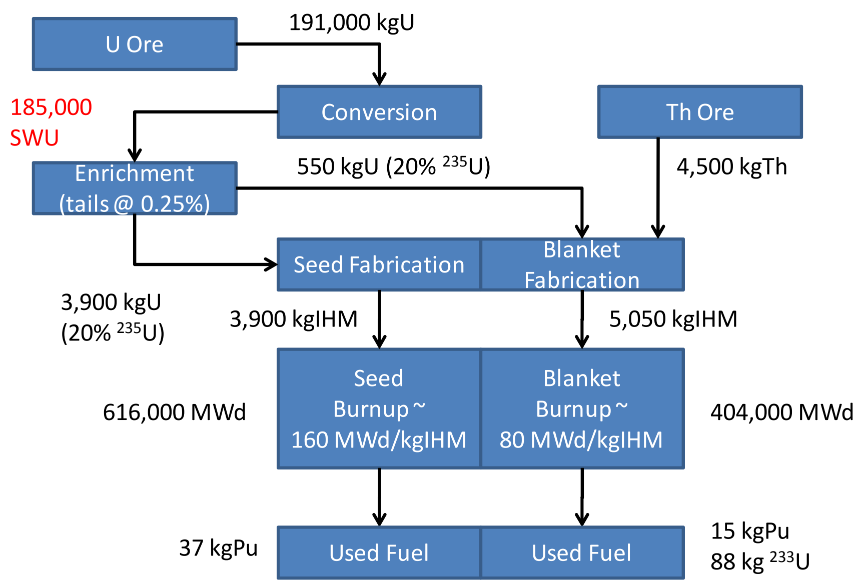

Figure A2-9. Annual mass flow chart for the once-through (Galperin, Radkowsky, Todosow 1999) concept in a 3400 MWt PWR.

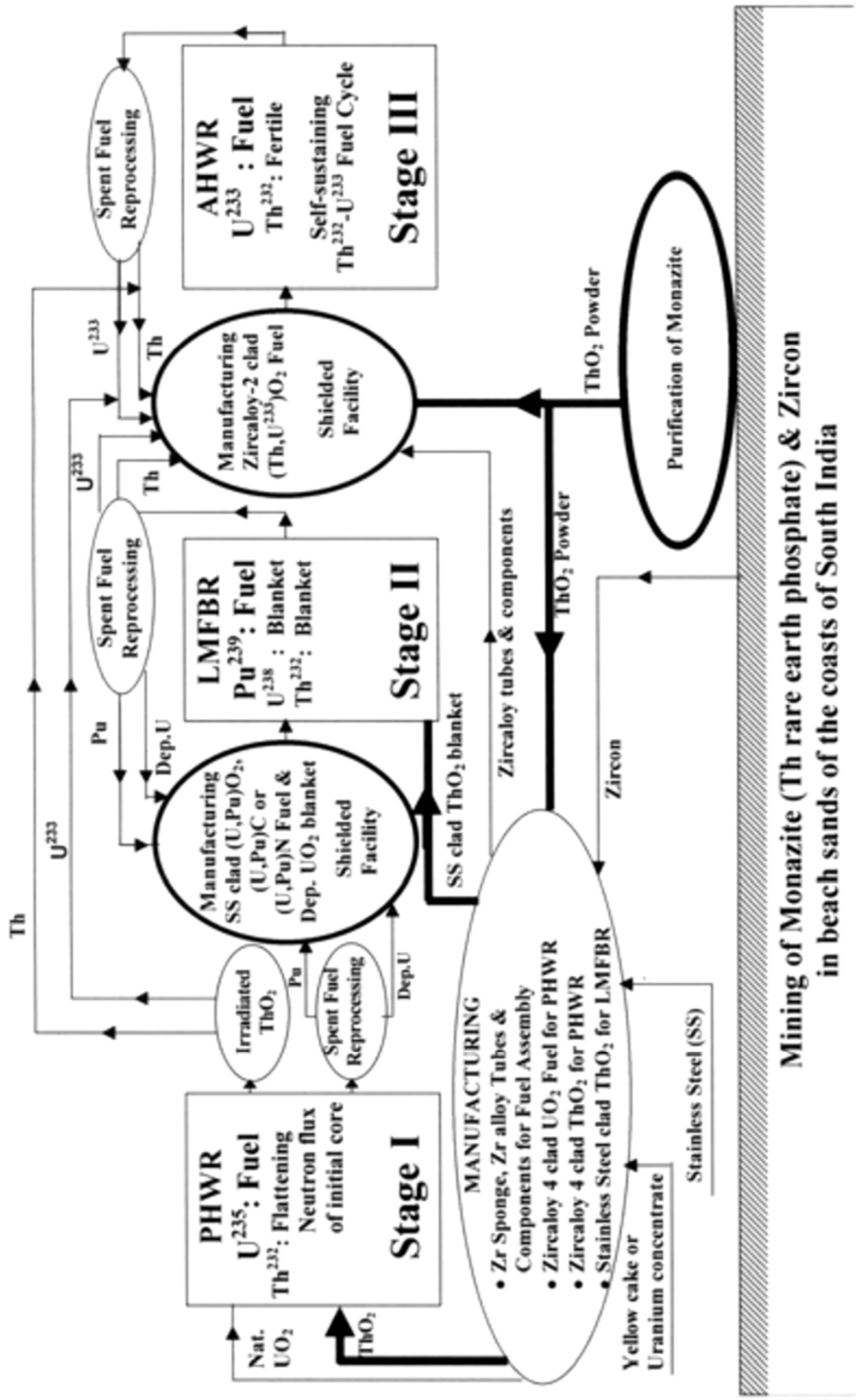

Figure A2-10. India’s three-stage path to a closed, breeding thorium cycle (IAEA 2005).

A2-10 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.

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, 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.

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.

A2-11 REFERENCES

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

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.

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

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.

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.