THE ECONOMICS OF REPROCESSING VS. DIRECT DISPOSAL OF SPENT NUCLEAR FUEL

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Appendix B. World Uranium Resources

B.1. Introduction

"There will always be ample fuel for nuclear reactors—we will never run out. The only questions are from where, and at what cost."

—James Graham, Chairman, Board of Governors, World Nuclear Fuel Market[211]

For decades, consideration of reprocessing, recycling, and breeding plutonium has been driven in significant part by concerns that resources of uranium would not be sufficient to support a growing nuclear energy system operating on a once-through cycle for long.[212] Advocates of reprocessing and breeding continue to argue that available resources of low-cost uranium are quite limited, making breeding and reprocessing essential in the relatively near term.[213] This raises the obvious question: how much uranium is likely to be economically recoverable in the future?

Uranium is roughly as common as tin or arsenic; Table B.1 shows typical concentrations in various media.[214] The total amount of uranium in the earth's crust is huge—on the order of 10^8 Mt. How much of this vast resource of uranium will be recoverable for use in nuclear energy depends on both technology and price. Advancing technology increases the recoverable resource in two ways: by offering additional ways to find resources, and by making it possible to mine and process uranium at lower cost, making available resources that would previously not have been economic to recover. Increasing prices also increase the available resource in two ways: by making lower-grade resources economic to recover, and by motivating additional exploration. (Increasing prices also tend to depress growth in demand, by encouraging more efficient use of

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[211] Remarks to the WNFM annual meeting, June 9, 2003.

[212] For a discussion from three decades ago (making the case that uranium resources were sufficient at that time to delay deployment of breeder reactors, which turned out to be more than correct), see John P. Holdren, "Uranium Availability and the Breeder Decision," *Energy Systems and Policy,* Vol. 1, No. 3, 1975.

[213] See, for example, U.S. Department of Energy, Office of Nuclear Energy, Science, and Technology, *Report to Congress on Advanced Fuel Cycle Initiative: The Future Path for Advanced Spent Fuel Treatment and Transmutation Research* (Washington, DC: January 2003, available as of December 16, 2003, at http://www.nuclear.gov/reports/AFCI_CongRpt2003.pdf), pp. I-4: uranium "is not an infinite resource. Expert organizations such as the World Nuclear Association project that between 2050 and 2080, nuclear power plants worldwide will encounter a serious shortage of the uranium needed to produce nuclear fuel." It is worth comparing this statement with the official World Nuclear Association (formerly the Uranium Institute) statement on "Supply of Uranium," available as of December 16, 2003 at http://www.world-nuclear.org/info/inf75.htm. That statement begins with the following sentences, emphasized in the original as the key points: "Uranium is a common metal, found in both rocks and seawater. Its availability to supply world energy needs is great both geologically and because of the technology for its use. All mineral resources are greater than commonly perceived." Later, it goes on to argue that: "Of course the resources of the earth are indeed finite, but… the limits of the supply of resources are so far away that the truism has no practical meaning."

[214] From Ian Hore-Lacy, *Nuclear Electricity* 7th ed. (Melbourne: Uranium Information Centre, Ltd, and World Nuclear Association, 2003, available as of December 16, 2003, at http://www.uic.com.au/ne.htm), Chapter 3. While this reference lists "high-grade" ores as being 2% uranium by weight, mines in Canada are now recovering ores that are more than 20% U_3O_8.

available resources—for example, by leaving lower assays in enrichment tails or using reactors with higher conversion ratios.)

Table B.1. Typical Uranium Concentrations

Medium	Average Concentration (ppm U)
High-grade ore	20,000
Low-grade ore	1,000
Granite	4
Sedimentary rock	2
Earth's continental crust	2.8
Seawater	0.003

Estimates of how much uranium would be available in the future at a given price are inherently uncertain, and there have been few serious attempts at a global assessment of total uranium resources (going beyond those already known to be available and recoverable) in recent decades. Indeed, for many years investment in exploration for uranium resources has been low, because low prices and the availability of large, already known uranium reserves suggested there was little money to be made in finding new deposits. As a result, as one analyst has noted, "predictions of the future availability of any mineral, including uranium, which are based on current cost and price data and current geological knowledge are likely to be extremely conservative."[215] The uranium resources that would likely be found if the price rose enough to motivate substantial investments in further exploration are likely to be far higher than today's resource estimates.

To understand the available estimates of how much uranium might ultimately be recoverable at various prices, it is important to understand the difference between "resources" and "reserves". The term "resources" refers to all of the quantities of a particular material that might ultimately be found and become economically recoverable, taking into account future improvements in the technologies of exploration and extraction, as well as future increases in prices. The term "reserves", by contrast, refers to those subsets of the resources that have been identified with high confidence and that are economically extractable at current prices using current technology. Reserves can be increased through exploration to identify additional economically extractable resources and by improvements in technology and operational practices to make economical the extraction of already identified (but previously uneconomical) resources.

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[215] Hore-Lacy, *Nuclear Electricity,* op. cit. It is worth noting that the statements on resources in this text which are quoted in this Appendix are all repeated verbatim in the World Nuclear Association statement "Supply of Uranium," op. cit.

Exploration is expensive; hence, industries have little incentive to find and characterize more than the amount of material expected to be needed in the next few decades. Investments in exploration typically are just sufficient to keep reserves constant or slowly growing as a multiple of annual consumption; if annual consumption exceeds annual additions to reserves over a prolonged period, with the result that the reserves fall significantly, the result is generally an increase in price that, in itself, converts some of the known but previously subeconomic resources into reserves and also calls forth an expanded exploration effort. The amount of material that will ultimately prove to be economically recoverable—termed "ultimately recoverable resources"—depends not only on the underlying geologic realities but also on the scope for improvement in the technologies of exploration, extraction, and use and on the amount by which the price of the material can rise before substitutes for it become economical and limit the demand.

Given these definitions and relationships, it is natural that published estimates of reserves would be quite accurate (limited mainly by uncertainties in the characterization of known deposits, by variations in analysts' assumptions about the capabilities of existing extractive technologies, and perhaps by corporate or national proprietary interests in less than full disclosure), while estimates of the ultimately recoverable resources would necessarily be much more uncertain. For example, estimates of the total amount of oil that ultimately will be economically recoverable range over a factor of two for today's technology, and over a factor of four or more assuming significant improvements in technology over the next two decades.[216] The uncertainties for natural gas are even larger.[217] The uncertainties for uranium—given the very low investments in exploration in recent decades, the very small efforts that have been made to integrate the resource information on a global basis, and the large factors by which uranium prices could rise before significantly affecting the economics of nuclear energy overall—are larger still.

B.2. Fallacy of the Traditional Economic Resource Model

Classical economic theory suggests that the price of non-renewable resources should rise over time, as the fixed available stock grows scarcer and more and more costly resources have to be used.[218] Forecasters relying on this model have routinely predicted that the uranium price would imminently begin a steady rise as resources began to become scarce, and these forecasters have just as routinely been proved wrong.

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[216] Hans-Holger Rogner, et al., "Energy Resources," chapter 5 in Jose Goldemberg, ed., *World Energy Assessment: Energy and the Challenge of Sustainability* (New York: United Nations Development Program, United Nations Department of Economic and Social Affairs, and World Energy Council, 2000), pp.139-144; available as of December 16, 2003 at http://stone.undp.org/undpweb/seed/wea/pdfs/chapter5.pdf.

[217] Ibid., pp. 144-147.

[218] For a useful discussion of the logical flaws of this classical model—still amazingly widely used, especially in projections of future uranium prices—see M.A. Adelman, "My Education in Mineral (Especially Oil) Economics," *Annual Review of Energy and Environment,* Vol. 22, 1997, pp. 13-46. Another excellent critique of the standard model (drawing on examples related to uranium resources) is Thomas L. Neff, "Are Energy Resources Inexhaustible?" presentation to the "Global Energy Prospects: Supply-Side Issues," London School of Economics and Political Science, November 11, 1985. Neff's basic answer is close to "yes," and with respect to uranium, he concludes "we were not so much captive of nature's limits as of our own in thinking about uranium reserves and resources."

The classical model fails to take into account the pace of discovery of new resources or the development of new technologies that reduce the cost of recovering material from less attractive sources. Because of these factors, the stock of resources available at a given extraction cost is *not* fixed, but increases for as long as technological improvements and new discoveries of material outpace the depletion of known high-quality deposits. And the fact is that, throughout the 20th century and for most mineral resources of interest, society has discovered new deposits and has improved the technologies of extraction at sufficient rates to more than compensate for the consumption of previously known reserves. In recent decades the ratio of current annual consumption to known reserves—the number of years left at current consumption rates—has *increased* for most types of mined resources, even as the rate of consumption has increased.[219] Over the last 25 years, this ratio has increased from 30 to 40 years for oil, and from 50 to 60 years for gas—despite increasing consumption.[220] Increases in price have stimulated the largest increases in reserves, but reserves have increased even in periods of constant or declining price.[221]

Technological improvements in resource extraction industries have been dramatic. The average U.S. coal miner in 1990 produced 8000 tons/year, compared to only 2500 tons/year in 1960; in the copper industry, output per miner increased at a remarkable rate of 8.6% per year from 1976 to 1987.[222] The result, for a wide range of non-renewable resources, has been prices that have been declining in real terms—the opposite of the classical model's prediction. In the United States, for example, the real price of a broad range of metals declined throughout the 20th century (just as the uranium price has been doing for the last 20 years).[223] There is little reason to believe that this trend will suddenly be reversed in the case of uranium, leading to the steady price rises throughout the 21st century that are often projected.

Even if the uranium price did begin to increase steadily, it does not appear likely to increase very quickly. For example, the Nuclear Energy Agency (NEA) of the Organization for Economic Cooperation and Development (OECD), in its last estimate of the future costs of the nuclear fuel cycle, assumed that uranium prices would increase 1.2% per year.[224] If we assume that prices rise to $45/kgU by 2020 (as commercial and military inventories are exhausted and prices have to rise to a level that will result in sufficient production to meet demand), and 1.2% per year thereafter, it would be well into the twenty-second century before uranium prices reached a level at which reprocessing at $1000/kgHM would be economically competitive.[225]

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[219] See, for example, Adelman, "My Education in Mineral (Especially Oil) Economics," op. cit.

[220] BP Statistical Review of World Energy 2003 (London: BP, June 2003); available as of December 16, 2003 at http://www.bp.com/files/16/statistical_review_1612.pdf.

[221] Ibid.

[222] Craig B. Andrews, "Mineral Sector Technologies: Policy Implications for Developing Countries" (Washington, DC: The World Bank, 1992).

[223] Daniel E. Sullivan, John L. Sznopek, and Lorie A. Wagner, "20th Century U.S. Mineral Prices Decline in Constant Dollars" (Washington DC: U.S. Geological Survey, Open File Report 00-389, available as of December 16, 2003 at http://pubs.usgs.gov/openfile/of00-389/of00-389.pdf).

[224] OECD Nuclear Energy Agency, *The Economics of the Nuclear Fuel Cycle* (Paris, France: OECD/NEA, 1994), p. 36.

[225] For a reprocessing price of $1000/kgHM, in chapter 2 we derive a central value of the breakeven uranium price of $370/kgU, with a lower limit (5 percent confidence interval) of $220/kgU. Assuming a price of $45/kgU in 2020

Clearly, technological changes over that long period will make such a simple calculation focused on today's LWR and reprocessing technologies irrelevant, but the calculation using today's figures is enough to indicate that it is likely to be quite some time before the economic disadvantage of reprocessing evaporates.

B.3. Estimates of Uranium Resources

The most widely available estimates of uranium resources are those in the "Red Book": a compendium of data on uranium resources from around the world, published by the NEA and the International Atomic Energy Agency (IAEA).[226]

The 2001 edition of the Red Book estimates that total world "conventional" resources available at less than $130/kgU amount to 16.2 million metric tons of uranium (MtU). This figure is the sum of "reasonably assured resources" (RAR, essentially what would be referred to as "reserves" if the uranium price were already $130/kgU), "estimated additional resources" (EAR, resources inferred to exist in extensions of known deposits and estimated to be economically harvestable at the indicated price[227]), and "speculative resources" (SR, resources that are expected to exist and to be discoverable and recoverable with existing technologies at a particular reported price level, based on geologic trends in particular areas).[228] If already-mined inventories are included—commercial inventories, excess defense inventories, and re-enrichment of depleted uranium tails that would be economic if the uranium price were to rise to the range of $130/kgU—the total figure rises to 17.1 MtU.[229] An international meeting sponsored by the IAEA in 2000 concluded that total resources available in this category likely amount to 20 MtU.[230]

Several points should be made about the Red Book total. First, because of the lack of incentive for substantial investments in uranium exploration in recent years, there are almost certainly large quantities of uranium that are not yet included in these estimates. Many countries remain lightly explored for uranium. Despite past exploration, modest additional investments have led in recent years to dramatic increases in estimates of available resources: in early 2001, for example, the Canadian firm Cameco increased its estimate of the uranium available at its McArthur River mine (the world's richest, with ore consisting of over 20% U_3O_8) by more than

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and an increase of 1.2 percent per year thereafter, uranium price would reach $220 and $370 in about 2150 and 2200, respectively.

[226] At this writing (mid-2003), the most recent edition is *Uranium 2001: Resources, Production, and Demand* (Paris, France: OECD Nuclear Energy Agency and International Atomic Energy Agency, 2002).

[227] Estimated additional resources (EAR) are reported in two categories, EAR-I and EAR-II. EAR-I represents additional resources for which the geologic evidence is direct, while EAR-II represents resources for which the evidence is more indirect. For more specific definitions—and how they correlate with how major uranium producing countries report their national resource estimates—see *Uranium 2001*, op. cit., pp. 13-15.

[228] RAR, EAR-I, EAR-II, and SR reported to be available at less than $130/kgU are, respectively, 2.853, 1.080, 2.332, and 9.939 MtU. See *Uranium 2001,* op. cit., pp. 21-27.

[229] R. Price and J.R. Blaise, "Nuclear Fuel Resources: Enough to Last?" *NEA News,* No. 20.2, 2002, available as of December 16, 2003 at http://www.nea.fr/html/pub/newsletter/2002/20-2-Nuclear_fuel_resources.pdf.

[230] "International Symposium on the Uranium Production Cycle and the Environment," October 2000, Vienna, reported in IAEA, "International Symposium Concluded That Uranium Supply for Nuclear Power is Secure," PR 2000/26 (Vienna, Austria: IAEA, October 6, 2000, available as of December 16, 2003 at http://www.iaea.org/worldatom/Press/P_release/2000/prn2600.shtml).

50 percent, based on analyses of drilling at that site over the previous few years.[231] It should be expected that this trend will continue in the future: the more energetically uranium firms look (when motivated to do so by increasing prices), the more uranium they will find.

Second, since uranium prices in recent years have been in the $20-40/kgU range, there has been no incentive to look for uranium in the higher-cost categories. Estimates of resources in these categories are therefore particularly uncertain, and very likely to be underestimates (probably by a large factor, as prices approaching $130/kgU would provoke intense exploration and technological improvements in recovering uranium from low-grade ores).

Third, the reported total figure has been increasing over time—despite the minimal global investments in uranium exploration in recent decades, and despite inflation eating away at the real value of the $130/kgU cap at which resources are reported—and can be expected to continue to do so in the future. The previous edition of the Red Book in 1999, for example, reported a comparable total of 15.4 MtU recoverable at less than $130/kgU, 800,000 tons less than the total reported two years later.

Fourth, because many countries do not report resources in all categories, these resources are omitted from the total. Only 28 countries report speculative resources, compared to 43 that report reasonably assured resources. Australia, for example, with some of the world's largest uranium resources, does not bother to estimate "speculative" resources because its better-known resources are so large already—but as the 2001 Red Book points out in its understated way, "countries, such as Australia, are considered to have significant resource potential in sparsely explored areas."[232] The Red Book table of speculative resources specifically notes that these totals are merely those that countries reported, and "do not represent a complete account of world undiscovered conventional resources."[233] Estimates based on extrapolations of Red Book data (to estimate resources in higher-cost and more speculative resource categories, and resources in countries for which no estimates are given) increase the total resource recoverable at costs less than or equal to $130/kgU by up to 45 percent, to about 24 MtU.

Fifth, this estimate includes only "conventional" resources—geologic resources where the uranium ore is rich enough to justify mining it by itself at the indicated price. In some cases, however, it may be attractive to produce uranium as a byproduct, as has been done with gold and phosphate mining. An additional 22 MtU are estimated to be available in phosphate deposits worldwide (though at very low concentrations),[234] and some noticeable fraction of this material may ultimately be economically recoverable as a byproduct of phosphate mining, as global demand for fertilizer continues to rise.

In short, despite the inclusion of "speculative resources" in the 17.1 MtU figure, there is a very high probability that the amount of uranium that will ultimately prove recoverable at or below $130/kgU will be significantly greater. Realistically, 17 MtU should be considered a

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[231] See Cameco, "Cameco Increases McArthur River Uranium Reserves," press release, January 25, 2001.

[232] *Uranium 2001,* op. cit., p. 26.

[233] *Uranium 2001,* op. cit., p. 27.

[234] *Uranium 2001,* op. cit., p. 28.

lower bound, not an upper bound, on the amount of uranium likely to be recoverable at $130/kgU.

Another way to approach the problem is to estimate the shape of the curve of resource availability as a function of price.[235] The limited available data make this estimation difficult. Based on geologic relationships, which indicate that exponentially larger resources are available at lower ore grades, it seems likely that the relationship between price and resources is roughly exponential. According to one industry observer, "a doubling of price from present levels could be expected to create about a tenfold increase in measured resources."[236] (The conservative nature of the Red Book figures, particularly in the higher cost ranges, can be judged from the fact that in its estimates of known conventional resources, doubling the price from $40/kgU to $80/kgU leads to only a 48% increase in resources estimated to be available.) If this correctly describes the relationship between price and resources, and if we calibrate the curve (*very* conservatively) by assuming that the 2.1 MtU of known resources reported in the 2001 edition of the Red Book as recoverable at $40/kgU represent the sum total of all resources in the world that will ever be recoverable at that price,[237] then the curve of resources as a function of price would be:

$$R = 2.1\left(\frac{p}{40}\right)^{\varepsilon} \tag{B.1}$$

where R is the total uranium resource (MtU) recoverable at price p ($/kgU) and ε is the long-term price elasticity of supply. If a doubling of price leads to a tenfold increase in resources, then $\varepsilon = \log(10)/\log(2) = 3.32$. By this crude estimate, doubling the price to $80/kgU would increase the recoverable resources to 21 MtU, and over 100 MtU would be available at $130/kgU.

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[235] More precisely, decreasing quality and accessibility of ores would be expected (if technological improvements do not keep pace) to lead to increases in extraction *cost.* The relationship between extraction cost and market price is complex, having to do with monopoly or cartel power; expectations of future prices; costs of bringing additional production on-line; costs of shifting additional resources to reserves; elasticities of demand; and more. The uranium market, which is characterized by utility buyers for whom uranium is only a small part of the cost of electricity production, but which are extremely concerned to ensure that fuel will be available when they needed it, is particularly sensitive to perceptions of future shortages or surpluses (and hence the price has been quite volatile over the last two decades). Nevertheless, in general in the uranium market, additional production capacity is brought on-line whenever prices rise high enough for it to be profitable for producers to bring that capacity on-line (taking into account the risks, including the risk that the price will decline again). Rather than saving their limited reserves for later production when prices might be higher, in other words, producers tend to act "as if their finite stocks were infinite" (Adelman, "My Education in Mineral (Especially Oil) Economics," op. cit.). If this behavior continues, and no durable cartel is formed, long-term average prices should be related to costs of production plus competitive rates of profit. Hereinafter we will refer only to price, with the notion that price will in general be such as to allow producers to extract the resource and earn a competitive profit.

[236] Hore-Lacy, *Nuclear Electricity,* op. cit.

[237] The resources available at this low price are the best-explored and best-characterized, and therefore the best available basis for calibration of such a relationship. Nevertheless, they are certain to be quite conservative. The Red Book figures in this low-cost category include only the best-characterized deposits (equivalent to reserves, rather than resources); it is virtually certain that additional investment in exploration would substantially increase the quantity of material reported as available at this cost. Moreover, the Red Book itself points out that the total quantity of resources available at $40/kgU or less "are higher than reported in the tables because certain countries do not report resource estimates, mainly for reasons of confidentiality." *Uranium 2001,* op. cit., p. 22.

One of the few serious attempts to estimate how much uranium is likely to be available worldwide concluded that a ten-fold reduction in ore concentration is associated with a 300-fold increase in available resources.[238] Although the authors made no attempt to associate costs of extraction with ore grades, if the phenomena reflected in equation (B.1) are similar to those examined in this geologic analysis, this would imply that doubling the price would make economical the exploitation of ores with uranium concentrations 2.5 times lower. This seems plausible, because not all of costs of uranium mining scale in direct proportion to the quantity of material that has to be mined and processed per ton of uranium recovered. If, at the other extreme, we assume that costs are inversely proportional to ore grade (as might be true at very low concentrations, when total costs became dominated by the amount of material mined and processed), the exponent ε in equation (B.1) would be 2.48, and the expected resource available for $130/kgU or less (using the same calibration technique) would be about 40 MtU.

More recently, the Generation IV fuel cycle crosscut group advising the Department of Energy's Office of Nuclear Energy, basing itself on the amounts of uranium recently estimated to be available in the United States at $30/kgU and $50/kgU, also predicted an exponential relationship between resources and price, and judged that the exponent ε in equation B.1 might be as low as 2.35.[239] Calibrating by the Red Book estimate of 2.1 MtU available at $40/kgU or less gives 34 MtU available at $130/kgU or less.[240] Table B.2 summarizes these estimates.

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[238] Kenneth S. Deffeyes and Ian D. MacGregor, "World Uranium Resources," *Scientific American,* January 1980. This article is based on Kenneth S. Deffeyes and Ian D. MacGregor, *Uranium Distribution in Mined Deposits and in the Earth's Crust: Final Report* GJBX-1(79) (Princeton, NJ: Department of Geological and Geophysical Sciences, Princeton University, 1978). It should be noted that Deffeyes is very far from being a wild-eyed resource optimist: his most recent book is *Hubbert's Peak: The Impending World Oil Shortage* (Princeton: Princeton University Press, 2001). For a quite different effort to assess world uranium resources, from the same period (which also concluded even then that resources were likely larger than now reported in the Red Book), see DeVerle P. Harris, "World Uranium Resources," *Annual Review of Energy* 1979 4:403-32. See also Neff, "Are Energy Resources Inexhaustible?" op. cit. More recently, see Thomas C. Pool, "Uranium Resources for Long-Term, Large-Scale Nuclear Power Requirements," *Nonrenewable Resources,* Vol. 3 No. 4, 1994, pp. 257-265. Like Neff, Pool is so confident that "availability of uranium resources is unlikely to place any major constraint on the future development of large-scale nuclear power" that he does not attempt to put a number on the total resource likely to be available.

[239] U.S. Department of Energy, Office of Nuclear Energy, *Generation IV Roadmap: Report of the Fuel Cycle Crosscut Group* (Washington, DC: DOE, March 18, 2001, available at http://www.ne.doe.gov/reports/GenIVRoadmapFCCG.pdf.), pp. 1-30.

[240] Inexplicably, the Generation IV fuel cycle crosscut group appears to mis-calibrate their equation, offering a constant of 77.4, which would result in resources at all reported prices far below those reported in the "Red Book." *Report of the Fuel Cycle Crosscut Group,* op. cit., pp. 1-30. This error is not an important one for the group's work, however, as the actual model they use for estimating uranium resources as a function of price is based on linear interpolation of the 1999 "Red Book" figures (see discussion on pp. A2-12-A2-14), and bears no relation to the exponential equation offered on pp. 1-30.

Table B.2. Uranium resource estimates, based on equation (B.1).

Source	**Elasticity of Supply, ε**	**R (MtU)** $p \leq$ **\$80/kgU**	**R (MtU)** $p \leq$ **\$130/kgU**
Uranium Information Centre	3.32	21	105
Deffeyes & MacGregor	2.48	12	40
Generation IV Group	2.35	11	34

These are very crude estimates of the relationship between price and available resources, based on extremely limited data. It may turn out that the curve does not have a continuously exponential shape, but rather has steeper and flatter portions.[241] More research on the actual quantity of uranium available worldwide in different price ranges is clearly needed. Nevertheless, the following points can be made about these relations:

- All of them suggest that the total amount of uranium recoverable at prices at or below $130/kgU is likely to be substantially larger than the amount reported in the Red Book – from two to six times larger.
- All of them use the very conservative estimate of the amount of uranium available at prices at or below $40/kgU. If world resources available at that price turn out to be twice as large, then the total resource available at less than $130/kgU also would be doubled.
- The relationships that result in smaller resource estimates are estimated based solely on geologic relationships, without including the likelihood that technology for recovering uranium at lower cost will improve in the future. As technological improvement is virtually certain, total resources recoverable at a given price decades in the future are likely to be larger than these estimates suggest—possibly enormously larger. The history of copper production is illustrative: as a result of improved technology, the real price declined by half from 1900 to 2000 despite a 25-fold increase in demand[242] and a decline in the average ore

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[241] For example, one model includes, in addition to costs increasing as ore grade decreases, costs at any given ore grade increasing roughly linearly with the amount of material at that grade that has been extracted, as the most accessible ores of that grade are mined and less accessible ores must be pursued. This more complex model predicts a flatter curve (and therefore lower expectations of total world resources extractable at higher prices). See Clifford E. Singer, "An Analytical Uranium Sources Model," in *Proceedings of the Technical Committee Meeting on Recent Developments in Uranium Resources, Production, and Demand* (Vienna, 10-13 June, 1997) (Vienna, Austria: International Atomic Energy Agency, 1998), pp. 27-38. We have based the discussion in this chapter on the simpler model based on exponential distributions of ore grade, in part because the existing experience with a range of mineral resources suggests that to date, extraction costs in real terms have not in fact been rising at given ore grades (perhaps because reductions in cost resulting from technological progress are counteracting increases in cost from exploitation of less accessible deposits). An examination of U.S. Geological Survey data covering a broad range of mined commodities over several decades, for example, demonstrates that real prices are typically flat or declining, and that price tends to decline slightly, rather than increasing, for those commodities for which annual demand has increased by the largest factor. (William Sailor, personal communication, 2003.)

[242] Kenneth E. Porter and Daniel L. Edelstein, "Copper Statistics," (Washington, DC: U.S. Geological Survey, August 28, 2002, available as of December 16, 2003 at http://minerals.usgs.gov/minerals/pubs/of01-006/copper.html). This estimate of a cut by a factor of two over the period is based on fitting a trend line to the statistics reported there; the actual ratio of the 2000 real price to the 1900 real price is 3.8, because there was a price

grade from 2 to 0.85 percent.[243] Despite the dramatic increase in annual consumption, there is little risk that the world will soon run out of copper. In the case of uranium, ores with concentrations as low as 4.5 parts per million—less than twice the average abundance in the earth's crust—have been recovered as byproducts from copper mines, at costs of less than \$52/kgU.[244]

Finally, it is important to note that \$130/kgU is considerably less than the price at which recycling would be economic. As indicated in chapter 2, a uranium price of more than \$360/kgU would likely be needed to make recycle at a reprocessing price of \$1000/kgHM economically competitive, which would likely increase recoverable resources by more than a factor of 10.

B.4. Uranium from Seawater

Even if, in the distant future, mineral ores are thoroughly depleted, it is not obvious that reprocessing and recycle would become economical. At the extreme of low-grade resources is the huge amount of uranium—4500 MtU—dissolved in the world's oceans at a concentration of about 3 parts per billion. Research has demonstrated that, using modern adsorbents, uranium can be recovered from seawater. The primary research programs in recent years have been in Japan, and, to a lesser extent, in France.

To date, only small amounts of uranium have been recovered by these methods. The resources devoted to these research efforts have been extremely small—probably a thousand times less than has been spent in recent years on R&D for reprocessing and breeding. Substantial further research and development would be needed to determine whether recovery of uranium from seawater could be done at an industrial scale and what the price of the recovered uranium might be.

The somewhat speculative estimates of the cost of recovering uranium from seawater that have been made in recent years have varied greatly from one study to another. Early approaches involved pumping seawater through the adsorbent. A pilot plant was built in Japan and operated for 2 years, but the pumping required more energy than would be provided by the recovered uranium, so this approach was abandoned.[245] Very high early cost estimates (well over \$1000/kgU) may have been associated with this pumped-water approach.

More recent approaches rely on ocean currents to move seawater through fixed arrays of adsorbents, with a ship collecting the uranium-bearing adsorbents for on-board processing or delivery to a shore-based processing facility. Japanese estimates for this latter approach in the

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dip around 2000 and a price spike around 1900. (The authors are grateful to William Sailor of Los Alamos National Laboratory for discussions on this point.)

[243] Oscar Groenveld, "The Technology Environment for the 21st Century—The Mining Industry," presentation to the Australian Academy of Technological Sciences and Engineering, 1998, available as of December 16, 2003 at http://www.atse.org.au/publications/symposia/proc-1998p1.htm.

[244] Described in Pool, "Uranium Resources for Long-Term, Large-Scale Nuclear Power Requirements," op. cit.

[245] This is briefly discussed, for example, in T. Kato, K. Okugawa, Y. Sugihara, and T. Matsumura, "Conceptual Design of Uranium Recovery Plant From Seawater," *Journal of the Thermal and Nuclear Power Engineering Society* (in Japanese), 50, 1999, pp. 71-77.

early to mid-1990s were in the range of $200-$260/kgU (then-year dollars).[246] In the late 1990s, both Japanese and French researchers put forward estimates as low as $100/kgU, though these were acknowledged to be highly uncertain and not backed by detailed engineering studies.[247] Such low total costs seem unlikely for facilities that must pay typical costs of money for privately owned facilities, as well as corporate income taxes. Since then, as might be expected, estimates have increased again. A Japanese paper from 1999 provides a detailed listing of the cost elements considered and arrives at an estimate of some $1200/kgU.[248] This paper appears to include unrealistically low rates of return on invested capital (at least for U.S. and European markets); incorporating financial assumptions comparable to those we have used for a regulated utility with a guaranteed rate of return would increase the estimate to over $1700/kgU. In 2000, French researchers put forward an estimate of roughly $250/kgU, but this is based on simple payback of capital with no return on investment and no payment of corporate taxes; using our financing assumptions for a regulated utility would almost double this estimate.[249] The most recent Japanese paper of which we are aware, published in 2001, argued for a cost in the range of 5-10 times the current cost of mined uranium; if we take that cost to be similar to current contract prices in the range of $35/kgU, this suggests a cost in the range of $175-$350/kgU, essentially comparable to the estimates for seawater uranium made a decade ago.[250] Faced with these varying estimates, the 2001 edition of the Red Book chose a value of $300/kgU as representative of current thinking.[251]

The cost of such an operation would be quite sensitive to the properties of the adsorbent material. The more uranium adsorbed per kilogram of adsorbent (and the shorter the time in the ocean required for this to occur), the cheaper the operation would be. Progress in developing improved adsorbent materials over the past decade has been substantial, and it is possible that there will be further progress in the future, reducing costs. Indeed, both French and Japanese researchers in this area have suggested that this is likely to be the case.

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[246] See Toru Hiraoka, "Nuclear Electricity Generation by Seawater Uranium," *Journal of the Atomic Energy Society of Japan* (in Japanese), Vol. 36, No. 7 (1994), pp. 644–645 (approximately $200/kgU), and H. Nobukawa et. al, "Development of a Floating Type System for Uranium Extraction from Seawater Using Sea Current and Wave Power," *Proceedings of the 4th International Offshore and Polar Engineering Conference*, Osaka, Japan, April 10-15, 1994, pp. 294-300 (approximately $260/kgU).

[247] Tadao Seguchi, director of material development at the Japan Atomic Energy Research Institute, estimated a cost of about $100/kgU (paper presented at Tokyo University-Harvard University workshop, Tokyo, May 23, 1998); Seguchi later put the cost at $100-$300/kgU in a plant producing 200 tU/yr, but emphasized that his specialty was adsorbent development, not cost estimation (personal communication to Richard L. Garwin, October 23, 1998). Jacques Foos, President of the CNAM Laboratory of Nuclear Sciences, prepared a report which, based on a review of the literature, suggested a range of $300-$370/kgU using then-existing technology, but suggested that this might be reduced to $80/kgU by the use of more advanced technologies being researched in his laboratory—while emphasizing that this estimate was very preliminary. (Foos, personal communication to J. Syrota, forwarded to Richard L. Garwin and Georges Charpak, April 3, 1997.)

[248] Kato, et al., "Conceptual Design of Uranium Recovery Plant From Seawater," op. cit.

[249] Jacques Foos, estimate described in detail in Richard L. Garwin, "Uranium From Seawater—A Green Fuel for the Future?" forthcoming.

[250] T. Sugo et al., "Recovery System For Uranium From Seawater With Fibrous Adsorbent and its Preliminary Cost Estimation," *Journal of the Atomic Energy Society of Japan* (in Japanese) 43 (10): 1010-1016, October 2001. See also the earlier T. Sugo and K. Saito, "Progress in Recovery Technology of Uranium From Seawater," *Journal of the Atomic Energy Society of Japan* (in Japanese), 36, 619–623, 1999.

[251] See *Uranium 2001,* op. cit. p. 28. The Generation IV crosscut team chose a value of $200/kgU, noting that such estimates are "highly speculative." *Report of the Fuel Cycle Crosscut Group,* op. cit. pp. 1-20, pp. 1-30.

The performance of current adsorbents is highly dependent on temperature, and they are thus effectively limited to warm surface waters. Moreover, to minimize costs, current concepts typically involve placement in currents close to the shore. However, horizontal and vertical mixing of the ocean would make seawater uranium accessible in warm surface waters at essentially constant concentration for many centuries, so long as the rate of extraction did not exceed ~2 MtU/y (30 times current consumption rates).[252]

These cost estimates do not include the value of the other metals that are co-recovered with the uranium. Current adsorbents used in Japan recover almost twice as much vanadium as uranium. Other metals such as cobalt, titanium, and molybdenum can also be co-recovered.[253] At today's prices, such co-recovered materials would pay for only a very small fraction of the cost of the recovery operation. If such materials became scarce and expensive in the future, however—as might occur by the time uranium became scarce and expensive enough for seawater extraction to be considered—the value of these co-recovered materials might be sufficient to substantially reduce the net per-kilogram recovery cost for uranium.

If uranium could be recovered from seawater economically, this would represent a vast energy resource for the future and could postpone for many centuries any need for breeding or reprocessing plutonium. But as the discussion above makes clear, it is not yet by any means certain whether uranium can be recovered from seawater at an industrial scale at a price below the reprocessing breakeven price. Given that all estimates of the cost of recovery from seawater are far above the current uranium price, industry has no incentive to fund further development of these concepts. We recommend a significant government program to explore both the total terrestrial resources likely to be recoverable as a function of price, and the possibilities for recovering uranium from seawater.

B.5. Uranium Consumption

If the above estimates of resource availability are matched to estimates of future uranium consumption, it is clear that uranium resources will not run out for a very long time to come. World uranium requirements in 2001 were roughly 64,000 tU.[254] Hence the Red Book estimate of 17 MtU available at less than $130/kgU represents more than 250 years' supply at current rates.

It is quite possible, however, that nuclear energy will grow in the future, and that if the world nuclear energy system relied primarily on once-through cycles without reprocessing, annual world uranium requirements would increase substantially. A recent study by the NEA on the potential contribution of nuclear energy to reducing greenhouse gas emissions envisioned

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[252] This is a rough estimate by the authors based on the flow rate between surface and deep ocean waters and vertical and horizontal mixing within surface waters, assuming the extraction of uranium is distributed throughout the five major ocean areas (north/south Pacific, north/south Atlantic, and Indian oceans).

[253] See, for example, Takanobu Sugo, "Uranium Recovery From Seawater" (Tokyo, Japan: Japan Atomic Energy Research Institute, 1999).

[254] *Uranium 2001,* p. 49.

three possible scenarios of future nuclear growth. The highest-growth scenario would consume only 5.6 MtU—one-third of the 17 MtU Red Book figure—by 2050.[255] While some official documents have raised the possibility of a uranium shortage arising even sooner, they are confusing the possibility that commercial investment in bringing mines on-line will not respond rapidly enough to imagined future nuclear energy growth—an issue of industrial structure and price signals in the market—with actually running out of low-cost uranium resources.[256]

Higher projections of nuclear growth are, of course, possible. In a detailed study of future energy scenarios in 1998, the World Energy Council (WEC) and the International Institute for Applied Systems Analysis (IIASA) outlined a wide range of scenarios for future energy supply, including nuclear energy.[257] "Case B," which the group considered the most plausible, was among the high-uranium-demand cases, and was used as the "base case" by the Generation IV fuel cycle crosscut team to examine the impact of large-scale future nuclear growth.[258] In Case B, global installed nuclear capacity would grow from 380 GWe in 1990 to 800 GWe in 2020, roughly 2000 GWe in 2050, and 5500 GWe in 2100. During 2000-2100, nuclear energy would provide 1.4 million terawatt-hours (TWh) of electricity.[259] How much uranium would be consumed by providing that much electricity using a once-through cycle depends on assumptions about what types of reactors are used, with what burnup, and how much U-235 is left in the depleted tails from enrichment plants. Assuming, quite conservatively, that the reactors are LWRs with an average burnup over the entire period of only 50 GWd/tHM, and a tails assay of 0.2% U-235, then 19 tU/TWh would be needed, for a total consumption of 26 MtU by 2100.[260] This is modestly higher than the 17 MtU estimated by the Red Book to be available at $130/kgU or less, but smaller than the 33 to 100 MtU given equation (B.1) using the values of ε discussed above. Other reactor systems designed for more efficient once-through uranium use could significantly reduce the uranium requirement in such a high-growth scenario.

In short, it seems very likely that uranium resources will continue to be available at substantially below the breakeven price for reprocessing at $1000/kgHM throughout the 21st century.

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[255] OECD Nuclear Energy Agency, *Nuclear Power and Climate Change* (Paris, France: OECD/NEA, 1998, available as of December 16, 2003 at http://www.nea.fr/html/ndd/climate/climate.pdf). The 5.6 MtU figure is likely to be an overestimate for the amount of nuclear energy generated in the scenario, as it does not appear to have included allowance for reduced tails assays as uranium became more expensive.

[256] See, for example, DOE, *Report to Congress on Advanced Fuel Cycle Initiative,* op. cit., pp. I-4-I-5, describing a study that indicated that production from presently planned and projected mines would only supply half of projected requirements in a "high case" scenario by 2030. The conclusion drawn that this "demonstrates" that "nuclear fuel from mined uranium could become a serious restraint on the growth potential of nuclear power in the not-too-distant future" is simply incorrect—as is the implication that any of the technologies being pursued in the Advanced Fuel Cycle Initiative could be developed and deployed in time to have much effect on supplies by 2030 if this were a serious problem.

[257] N. Nakicenovic, A. Grübler, and A. McDonald, eds., *Global Energy Perspectives* (Cambridge, UK: Cambridge University Press, 1998).

[258] *Report of the Fuel Cycle Crosscut Group,* op. cit. pp. 1-33.

[259] Calculated using data available at International Institute of Applied Systems Analysis, "Global Energy Perspectives Database," available as of December 16, 2003 at http://www.iiasa.ac.at/cgi-bin/ecs/book_dyn/bookcnt.py.

[260] Steve Fetter, "Comments on 'Report of the Fuel Cycle Crosscut Group,'" unpublished memorandum, April 2002. A tails assay of 0.2% would minimize total fuel cycle costs when uranium price is about 1.3 times enrichment price (e.g., $130/kgU for $100/SWU).