Uranium Resources for the Long Term

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In discussions of the future growth of nuclear energy, much attention is given to the sustainability of uranium resources. Indeed, consideration of reprocessing, recycling, and breeder reactors 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. Advocates of reprocessing and breeding continue to argue that available resources of low-cost uranium are limited, making breeding and reprocessing essential sooner rather than later.

A good starting point for such discussions is the contribution of uranium to the cost of nuclear-generated electricity. In 2005, the average price paid by U.S. nuclear generators was \$37 per kilogram of natural uranium (kgU; see figure 1). About 8 kgU are required to produce 1 kilogram of low-enriched uranium (LEU), capable of producing an average of 50 megawatt-days of thermal energy in a light-water reactor (LWR), which is converted to electricity with an efficiency of 32 percent.[1] The contribution of uranium to the cost of LWR electricity is therefore

$$\left[\frac{\$37}{\mathrm{kg_U}}\right]\left[\frac{8\ \mathrm{kg_U}}{\mathrm{kg_{LEU}}}\right]\left[\frac{\mathrm{kg_{LEU}}}{50\ \mathrm{MW_{th}d}}\right]\left[\frac{\mathrm{MW_{th}}}{0.32\ \mathrm{MW_e}}\right]\left[\frac{\mathrm{d}}{24\ \mathrm{h}}\right] = 0.8\frac{\$}{\mathrm{MWh}}$$

For comparison, the cost of electricity produced by an advanced LWR is estimated at about \$70/MWh. Thus, uranium currently contributes a bit more than 1 percent to the cost of nuclear-generated electricity. It follows that the cost of uranium could increase five or even ten fold, to \$200 to \$400/kgU, with modest effect on the cost of electricity. As we will show below, these large increases in price would produce very much larger increases in available uranium resource—increases sufficient to support an inefficient once-through fuel cycle for through the end of the century and beyond, even in the face of rapid growth of nuclear energy.

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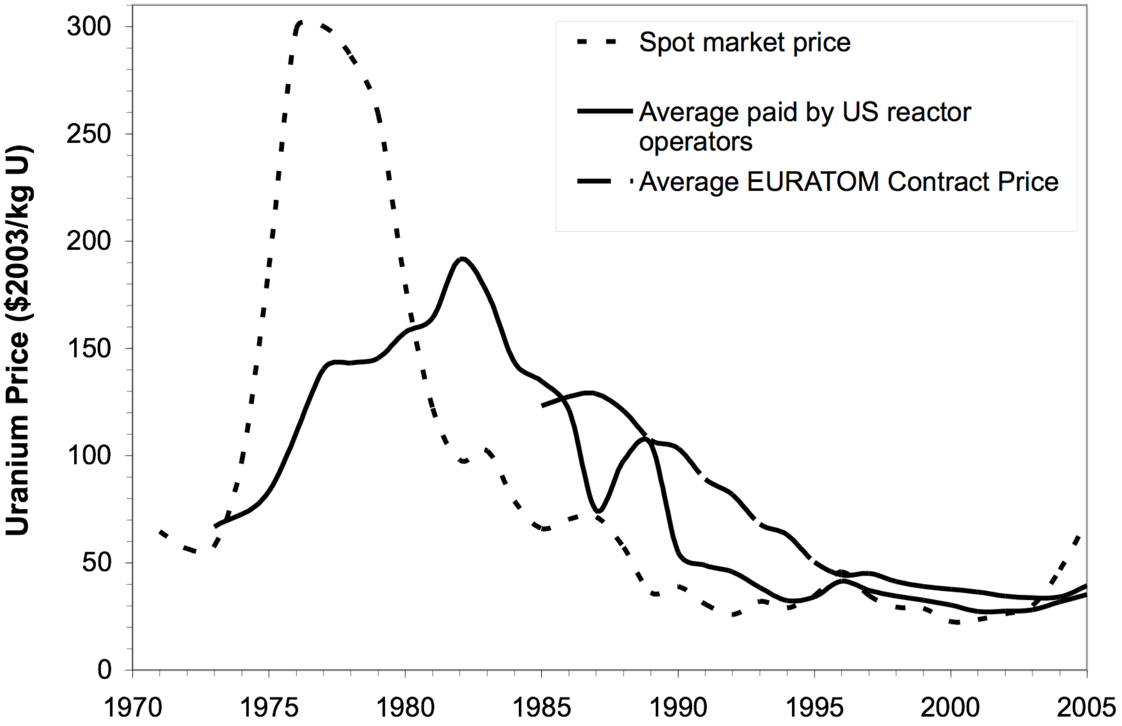
[1] Assumes product and tails assays of 4.4 and 0.2 percent uranium-235, respectively.

Figure 1. The spot market price for uranium, 1971-2005, the average price paid by U.S. reactor operators, and the average contract price reported by EURATOM.



Uranium Resources

Uranium is roughly as common as tin or arsenic. The total amount of uranium in the earth's crust is huge—on the order of 10^8 million metric tons of uranium (MtU). 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.

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. 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.

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.[2] The uncertainties for natural gas are even larger. 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.

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[2] 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 July 29, 2003 at http://stone.undp.org/undpweb/seed/wea/pdfs/chapter5.pdf.

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 scarce and more costly resources are extracted. But this model fails to take into account the discovery of new resources and the development of new technologies that reduce the cost of recovering material from less attractive sources. 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.[3] Increases in price have stimulated the largest increases in reserves, but reserves have increased even in periods of constant or declining price.

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.[4] 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. The real price as most metals has fallen with cumulative extraction, because new deposits were discovered and the technologies of extraction improved at rates more than sufficient to compensate for the consumption of previously known reserves.[5] 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.

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).[6]

The 2001 edition of the Red Book estimates that total world "conventional" resources available at less than $130/kgU amount to 16.2 MtU. This figure is the sum of "reasonably assured resources," "estimated additional resources," and "speculative resources." 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.[7] An international meeting sponsored by the IAEA in 2000 concluded that total resources available in this category likely amount to 20 MtU.[8] We

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[3] Adelman, "My Education in Mineral (Especially Oil) Economics," *Annual Review of Energy and Environment,* Vol. 22, 1997, pp. 13-46.

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

[5] 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 July 29, 2003 at http://pubs.usgs.gov/openfile/of00-389/of00-389.pdf).

[6] *Uranium 2001: Resources, Production, and Demand* (Paris, France: OECD Nuclear Energy Agency and International Atomic Energy Agency, 2002).

[7] R. Price and J.R. Blaise, "Nuclear Fuel Resources: Enough to Last?" *NEA News,* No. 20.2, 2002, available as of June 24, 2003 at http://www.nea.fr/html/pub/newsletter/2002/20-2-Nuclear_fuel_resources.pdf.

[8] "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

chose \$130/kgU as a baseline, because elsewhere we have shown that this is the minimum uranium price at which breeder reactors would become economically attractive, even if they cost as LWRs per kilowatt.[9]

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 50 percent, based on analyses of drilling at that site over the previous few years.[10] 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—particularly in higher-cost categories.

Second, many countries do not report resources in all categories. 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."[11] 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." Estimates based on extrapolations of Red Book data increase the total resource recoverable at costs less than or equal to \$130/kgU by about 45 percent, to 24 MtU.

Third, 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),[12] 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 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 lower bound on the amount of uranium likely to be recoverable at \$130/kgU.

2000/26 (Vienna, Austria: IAEA, October 6, 2000, available as of June 24, 2003 at http://www.iaea.org/worldatom/Press/P_release/2000/prn2600.shtml).

[9] Matthew Bunn, Steve Fetter, John P. Holdren and Bob van der Zwaan, "The Economics of Reprocessing vs. Direct Disposal of Spent Nuclear Fuel," Nuclear Technology, Vol. 150, No. 3 (June 2005).

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

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

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

Another way to approach the problem is to estimate the shape of the curve of resource availability as a function of price. Geologic data indicates that the total amount of uranium increases exponentially with decreasing ore grade. According to one industry observer, "a doubling of price from present levels could be expected to create about a tenfold increase in measured resources."[13] If this correctly describes the relationship between price and resources, and if we (*very* conservatively) assume that the 2.1 MtU reported in the Red Book as are recoverable at $40/kgU is the sum total of all uranium that will ever be recoverable at that price, then the total uranium resource R (MtU) recoverable at price p ($/kgU) would be

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

where ε is the long-term elasticity of uranium supply. If a doubling of price leads to a tenfold increase in resources, then $\varepsilon = 3.3$. 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.

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.[14] If we assume that costs are inversely proportional to ore grade (as might be true at low concentrations, when total costs became dominated by the amount of material mined and processed), then $\varepsilon = 2.5$, and the expected resource available at $130/kgU or less 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 ε might be as low as 2.35.[15] Calibrating by the Red Book estimate of 2.1 MtU available at $40/kgU or less gives 33 MtU available at $130/kgU or less.

These are very crude estimates of the relationship between price and available resources, based on extremely limited data. Nevertheless, all of these estimates 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.

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

[14] Kenneth S. Deffeyes and Ian D. MacGregor, "World Uranium Resources," *Scientific American,* January 1980. For a quite different effort to assess world uranium resources, see DeVerle P. Harris, "World Uranium Resources," *Annual Review of Energy* 1979 4:403-32. See also Neff, "Are Energy Resources Inexhaustible?" and 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.

[15] 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.), p. 1-30.

Uranium From Seawater

A huge amount of uranium—4500 MtU—is dissolved in the world's oceans at a concentration of about 3 parts per billion. Using modern adsorbents, uranium can be recovered from seawater. To date, only small amounts of uranium have been recovered by these methods. The resources devoted to these research efforts have been tiny compared to that spent on R&D for reprocessing and breeder reactors. 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.

Early approaches to recovering uranium involved pumping seawater through the adsorbent, but the pumping required more energy than would be provided by the recovered uranium. More recent approaches rely on ocean currents to move seawater through fixed arrays of adsorbents. The performance of current adsorbents is highly dependent on temperature, and they are thus effectively limited to warm surface waters. To minimize costs, adsorbents would be placed 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.

The Gen-IV Fuel Cycle Crosscut Report estimated the cost of seawater uranium at $240 to 450/kgU. 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.[16] If such metals 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. But it is not yet by any means certain whether uranium can be recovered economically from seawater at an industrial scale at a price below the reprocessing breakeven price. 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.

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. Current world uranium requirements are about 68,000 tU/y. Hence the Red Book estimate of 17 MtU available at less than $130/kgU represents a 250 years supply at current rates of consumption.

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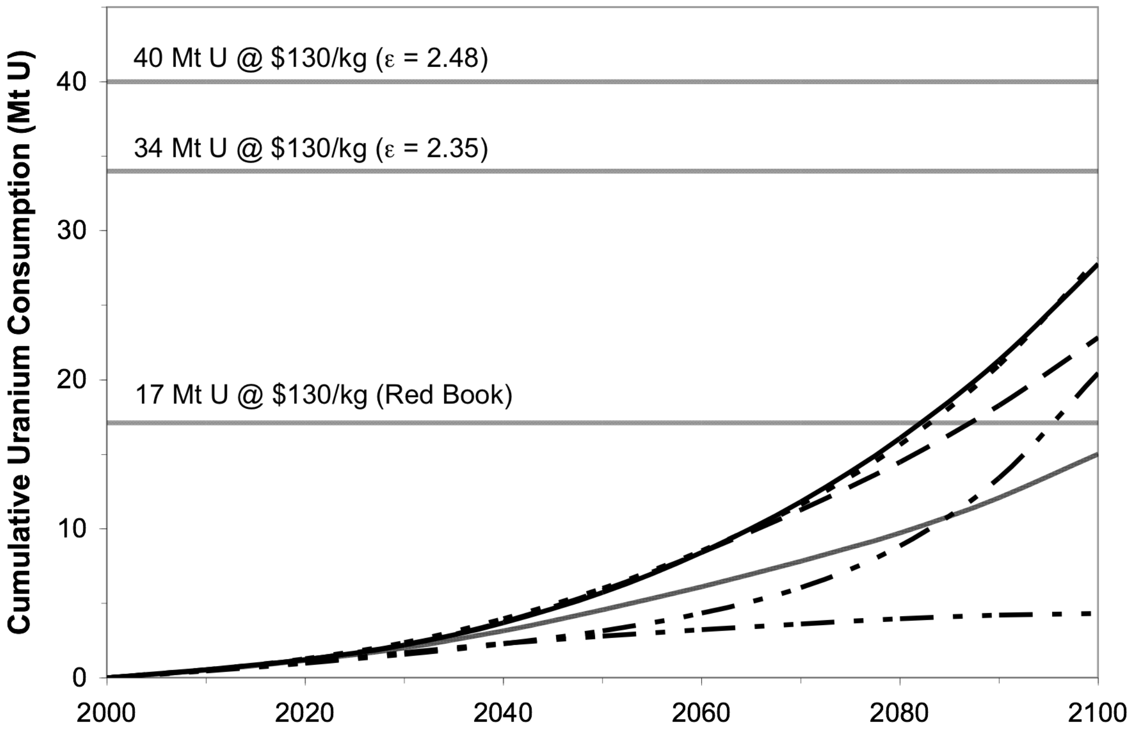
[16] Takanobu Sugo, "Uranium Recovery From Seawater" (Tokyo, Japan: Japan Atomic Energy Research Institute, 1999).

It is quite possible that nuclear energy will grow in the future. 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.[17] "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.[18] In Case B, global installed nuclear capacity would grow to 800 GWe in 2020, roughly 2000 GWe in 2050, and 5500 GWe in 2100. Assuming, quite conservatively, that the reactors are LWRs with an average burnup over the entire period of only 50 MWd/t, 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. 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 using the values of ε discussed above.

Thus, it seems very likely that uranium resources available at prices that would have little impact on the cost of nuclear-generated electricity are sufficient to support a once-through fuel cycle for the next century.

Figure 2. Estimated consumption of uranium in the WEC/IIASA scenarios assuming once-through LWRs, compared to estimated uranium resources.



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

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