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Market Power in Uranium Enrichment

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Four firms dominate the international uranium enrichment market. Simultaneously, the nations that host enrichment facilities strongly discourage other nations from developing enrichment capacity, given its potential use in nuclear weapons production. Therefore, these four firms benefit from the exercise of national power to prevent entry into this market. This paper shows that these firms also benefit from increasing returns to scale. In similar national situations, this industry would be regulated or nationalized. This is because free markets do not necessarily lead to a socially optimal long-run equilibrium where the industry is *necessarily concentrated*, such that there is no proliferating entry, but is *sufficiently diverse*, so that no one national group can dictate prices, contract terms, or non-proliferation policy. Therefore, some form of international regulation might be necessary to discourage enrichment technology proliferation and assure enrichment supply at reasonable prices.

THE INTERNATIONAL URANIUM ENRICHMENT MARKET

In the debate on how to assure nuclear fuel (such that nations considering the building of nuclear power plants do not also have to consider building uranium enrichment plants), there is little discussion of whether free

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(unregulated) markets can provide assurances that enrichment capacity will be available to all customers at *reasonable prices*.

There are at least four markets in the front-end of the nuclear fuel cycle that must be reviewed to determine assurance of supply: (1) uranium mining and milling, (2) uranium conversion, (3) uranium enrichment, and (4) nuclear fuel fabrication. Rothwell finds that the nuclear fuel fabrication of low-enriched uranium into light-water reactor fuel rods is a competitive industry with barriers to entry to discourage investment in fuel fabrication by nations with small nuclear industries.[1] Future papers will examine competition in uranium mining and milling[2] and uranium conversion. This paper examines whether market forces in the uranium enrichment market can lead both to economic efficiency and to socially optimal levels of assured alternative sources of supply, given the risk of enrichment technology spread.

Four firms now dominate the international uranium enrichment market: United States Enrichment Corporation (USEC, which was privatized in the 1990s), TENEX/Rosatom (Russia), Eurodif/Areva (France), and Urenco (with government-owned plants in Germany, the Netherlands, and the United Kingdom). Until the 1980s, the United States (through the Atomic Energy Commission) monopolized the Western enrichment market with gaseous diffusion and Russia monopolized the Eastern market. The U.S. commercial dominance of gaseous diffusion ended with the entry of Eurodif, a consortium of countries with France as the diffusion technology provider and only producer. However since the 1980s, firms using gas centrifuge technology, including those in Russia and the British-Dutch-German Urenco, have captured increasing market share. USEC's share of enrichment capacity declined from 39% in 1995 to 14% in 2008, as earlier diffusion facilities (at Oak Ridge, TN, and Portsmith, OH) were retired.

Table 1 shows changes in capacity shares over the last decade. (Not all of this capacity *directly* serves the fuel market, as discussed in the next section; for example, Russia is using excess capacity to slightly enrich uranium to mix with down-blended, weapons-grade, highly-enriched uranium.) The

Table 1: International uranium enrichment capacity shares, 1995–2008.

Country	Owner	Share 1995	Share 2001	Share 2005	Share 2008	"Euro" 2008
HHI		2,900	2,800	2,900	3,000	3,600
US	USEC	39%	23%	16%	14%	14%
Russia	Tenex	29%	41%	45%	47%	47%
France	Areva	22%	22%	22%	20%	35%
European	Urenco	7%	11%	14%	15%	
Japan	JNFL	2%	2%	2%	2%	2%
China	CNNC	1%	2%	2%	1%	1%

Herfindahl-Hirschman Index (HHI) measures the degree of concentration in an industry. HHI is the sum of the squares of the percentage market shares in an industry. HHI ranges from 100 with an industry of 100 equal-sized firms, to 5,000 in an industry with a duopoly, to 10,000 for a monopoly. The U.S. Department of Justice and the Federal Trade Commission has considered industries with HHIs above 1,800 to be "concentrated," and would discourage a merger in these industries if the HHI were to increase by more than 100 points:

> Markets in which the HHI is between 1000 and 1800 points are considered to be moderately concentrated, and those in which the HHI is in excess of 1800 points are considered to be concentrated. Transactions that increase the HHI by more than 100 points in concentrated markets presumptively raise antitrust concerns under the Horizontal Merger Guidelines issued by the U.S. Department of Justice and the Federal Trade Commission.[3]

Although highly concentrated, from 1995 to 2008, the HHI changed little as USEC facilities were retired and Russian capacity increased. In the last column of Table 1, the HHI is calculated under the assumption that Areva and Urenco ("Euro") do not compete (because they are now using the same centrifuge manufacturer), the HHI would increase by 600 points: Under this assumption of investment coordination, the industry would be even more concentrated.

During the next decade, older diffusion capacity will be replaced by newer centrifuge capacity in France and the United States. In France, Eurodif (a member of the Areva group) has partnered with Urenco to produce centrifuges through the Enrichment Technology Company (ETC). In the United States, the Department of Energy (U.S. DOE) has partnered with USEC to develop a new generation of centrifuge to replace USEC's diffusion capacity. Testing of the first cascade began in September 2007, although plant completion could depend on loan guarantees from the U.S. DOE. Also, Urenco is building centrifuge capacity in New Mexico, and Areva is building centrifuge capacity in Idaho.

Further, the Brazilian INB (Indústrias Nucleares do Brasil) is building a small enrichment facility at its Resende integrated-nuclear-fuel-cycle site to assure the fuel supply of its two nuclear power plants.[4] Argentina, which has two small, de-activated enrichment facilities, is considering re-activating them. South Africa is interested in refurbishing and expanding its uranium enrichment facility at Pelindaba. An Australian firm, Silex, has licensed its technology to GLE (a partnership of General Electric/Hitachi and Canadian Cameco) to build a prototype laser enrichment facility in North Carolina. With diffusion facility retirements and new centrifuge facilities coming online, market capacity, price level, and price volatility will be uncertain during the coming decade. Can we be assured that an international free market in uranium enrichment will lead to socially-optimal levels of enrichment capacity over the foreseeable future?

Neo-classical economic theory shows that society is better off when market prices equal the cost of production, including a reasonable (risk-adjusted) return on capital. When prices do not reflect the cost of production, economists conclude the market has "failed," because it has failed to achieve the socially-optimal level of output or investment. Markets fail for at least four reasons: (1) in industries where there are strong increasing returns to scale (also known as positive scale economies), the largest firms can increase market share to monopoly or near monopoly levels, then raise prices, for example, in software, particularly in operating systems; (2) where unpriced inputs or outputs, known as externalities, influence another producer or consumer's profits or well-being, for example, greenhouse gas production, which is now not priced; (3) where consumers cannot be excluded from consumption, for example, from national security; and (4) where there is systematic asymmetric information between the buyer and seller, for example in markets where buyers cannot know the riskiness of the seller's financial instruments.

While there might be more than one source of market failure in the international uranium enrichment market (for example, the unpriced proliferation externality associated with enrichment technology), this paper will focus on the issue of increasing returns to scale. With increasing returns, (1) small producers (such as new entrants) have little economic incentive to enter to compete with established and growing larger producers, and (2) larger producers can eventually drive smaller rivals from the market. This leads to market power where prices can be higher than costs, or where other concessions can be extracted, e.g., the assumption of price risk by the customer, or market power can be leveraged into other markets, such as nuclear reactor sales.

However in the enrichment industry, increasing returns provide a barrier to entry, thus increasing the industry's proliferation resistance, and reducing the social cost of the proliferation externality. Therefore, increasing returns in enrichment reduce both proliferation and market price discipline. Given increasing returns, the economic issue is whether free markets in uranium enrichment can assure optimal long-run levels of investment *and* nonproliferation.

Most enrichment industry observers assume there are increasing returns to scale. (Although this paper focuses on estimating returns to scale at the level of SWU costs, increasing returns could arise in centrifuge manufacturing; however, without a detailed description of structure and equipment costs for a cross-section of facilities, it is not possible to separate the various sources of increasing returns to scale in capital.) The Appendix finds there are increasing returns, and proposes a top-down, microeconomic-cost-engineering model of the industry. The next section describes the emerging duopoly in the international uranium enrichment market, and uses this model to show that if enrichment prices were determined by competitive markets, prices would fall with diffusion capacity retirement. If prices remain high, if a monopoly develops, or if enrichment technology proliferates from current enrichers (e.g., from Urenco), free markets will not lead to socially optimal outcomes. Hence, the final section, describing the implications of this duopoly, argues that some form of international market intervention (beyond the patchwork of national subsidies and international treaties) could be necessary to insure an optimal diversity of non-proliferating capacity investment and prices near production cost.[5] Given the small size of economic profits in this industry and the consequences of proliferation, there is little to be lost in terms of economic efficiency if enrichment price regulation eases the creation of non-proliferation agreements with nations considering possible entry into uranium enrichment.

AN EMERGING DUOPOLY IN THE INTERNATIONAL URANIUM ENRICHMENT MARKET

To increase the percentage of fissile uranium, Uranium-235, from approximately 0.7%, natural uranium oxide ("yellowcake") is enriched to a higher percentage, e.g., 3 to 5%. Enrichment is now done commercially using two methods: gaseous diffusion and gas centrifuge. Between 1991 and 2008, the real spot price of uranium enrichment, measured in Separative Work Units (SWU) doubled from $80 to $160 in 2008 dollars. (SWU are measured in kilograms, kgU, or Metric Tons of Uranium, MTU.)[6] See Figure 1. As discussed in the Appendix, the cost of gaseous diffusion enrichment is driven by the price of electricity. As

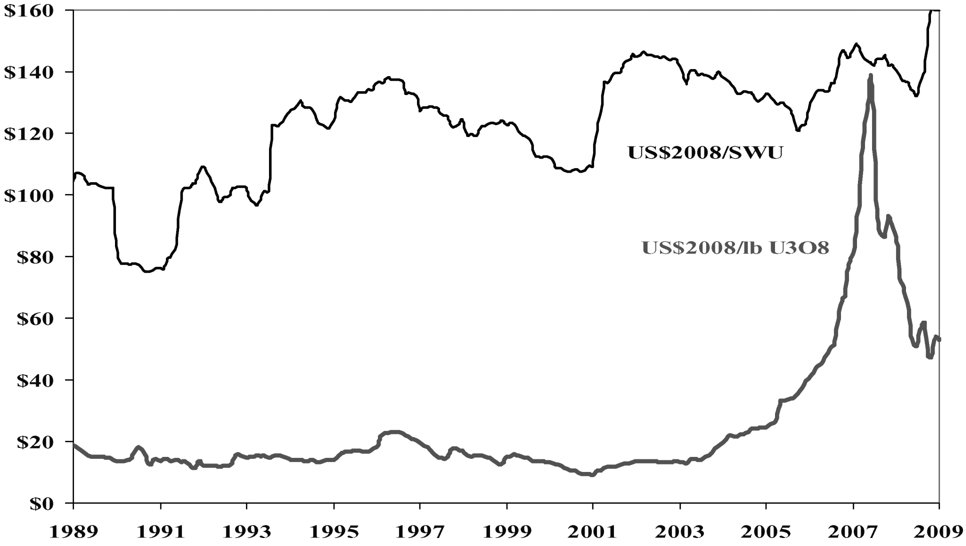

Figure 1: Spot prices for SWU and uranium, 1989–2009.

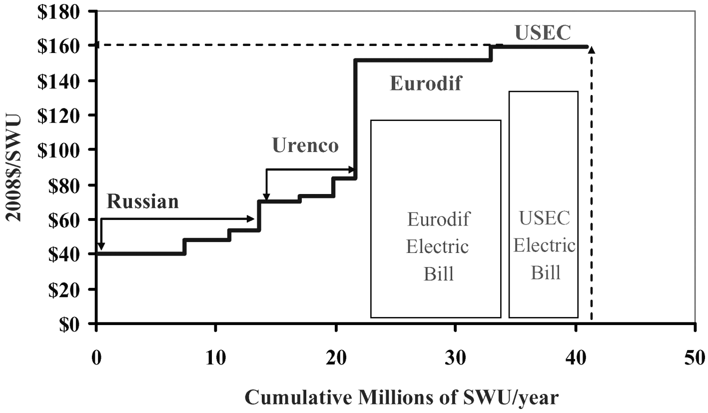

Figure 2: Supply of uranium enrichment services, 2010.

the price of electricity has risen, the cost of diffusion enrichment has risen above the cost of centrifuge enrichment, making gaseous diffusion plants the marginal producers, i.e., those that supply the last segment of demand. As the marginal producers, gaseous diffusion enrichment suppliers' costs (primarily the cost of electricity) are highly correlated with the spot market price.

To represent this market, the Appendix estimates average SWU cost in 2008 dollars. (These estimates are used to illustrate the international SWU market and are based on statistical results, thus there could be an error of ±10 to 20 percent based on the estimation's standard errors. Construction costs are deflated following the U.S. GDP implicit price deflator. Electricity prices are deflated following the U.S. Producer Price Index for Electricity Generation, Distribution, and Transmission.) Using long-run levelized cost as a proxy for long-run marginal cost, levelized costs are used to construct SWU supply curves for 2010 (Figure 2) and 2020 (Figure 3). 2020 was chosen because the Russia-United States blend down agreement will be terminated, the gaseous diffusion capacity will be retired, and the enrichment capacity under current planning and construction should be completed.

In Figure 2 (for 2010) it is assumed that Russian production is limited such that the Novouralsk facility (with 12.45M SWU per year) is not competing in the international market (due to agreements associated with blending down highly-enriched uranium and domestic commitments).[7] In Figure 2, about one quarter of the international enrichment market (Russian) is low cost (less than $60), one quarter (Urenco) is moderate cost (between $60 and $100), and one half the market (gaseous diffusion) is high cost (more than $100). With requirements around 40M (million) SWU (approximately 120,000 SWU per GW per year for 333 GW worldwide), the market price is determined where demand is satisfied by the highest cost producers (those with gaseous diffusion technology) at approximately $160/SWU (in 2008 dollars). (Of course, cheaper

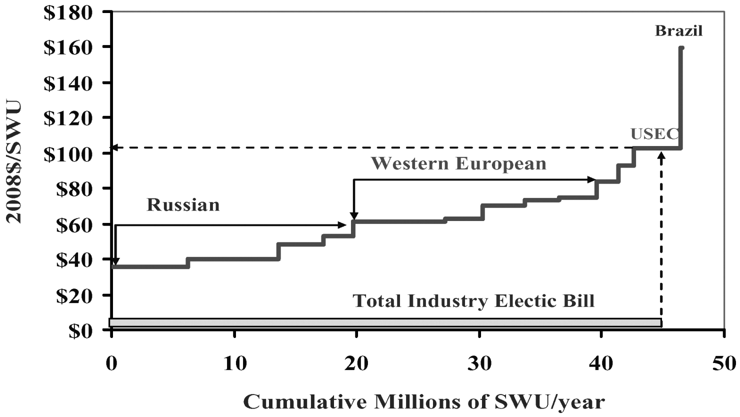

Figure 3: Supply of uranium enrichment services, 2020.

producers could undercut Eurodif's and USEC's price with proprietary long-term contracts; so contract prices are not necessarily equal to spot market prices, and revenues and economic profits could be *much lower* than suggested here.)

With diffusion capacity retirement and no international constraints on Russian participation in the market, the supply curve for enrichment services could shift by 2020 to a situation more like that in Figure 3.[8] Assuming growth of 12.5 percent to 45M SWU, world requirements could be satisfied by all enrichers, and maximum total revenues would be approximately $4,500M (in 2008 dollars).[9] However, as today, USEC could be the marginal producer, so a competitive market should equilibrate to cover USEC's new levelized production costs (e.g., $100/SWU in 2008 dollars). This suggests a price drop of almost 40 percent, and a savings to consumers. However, the industrial concentration in 2020, as measured by the HHI, would jump to 3,500 if Areva and Urenco are competing, or to 4,200 if Areva and Urenco are not competing. If they are not competing, the industry approaches the concentration of a duopoly (HHI = 5,000) with the Russians and Europeans dominating the uranium enrichment market. (This analysis does not include Urenco capacity increases by replacing the TC-12 centrifuge with the TC-21 centrifuge.)[10]

Therefore, as diffusion capacity is retired and prices fall to reflect a decline in costs (following competitive market forces), because of their more mature technology, Russia and the Europeans could earn economic profits, but Japan's Rokkasho and USEC's ACP might not earn anything above their reasonable capital and production costs. Anticipation of this situation could make financing for USEC difficult to acquire at a cost of capital that will allow them to be competitive, particularly if credit is tight and their credit rating continues to decline. The Great Recession could slow ACP completion, thus postponing the retirement of USEC's diffusion capacity, and supporting a higher market price.

Russia is building additional enrichment capacity. One method for increasing enrichment market share is the creation of the International Uranium Enrichment Center (IUEC) in Angarsk, Siberia. The Angarsk enrichment and conversion plants have been combined with Kazakhstan's uranium mines. A Kazakhstan fuel pellet plant could be upgraded to provide nuclear fuel fabrication services. If the IUEC could provide nuclear fuel at a lower market price, it could increase its nuclear fuel market share, and thus Russia's enrichment market share.

IMPLICATIONS OF ENRICHMENT DUOPOLY EMERGENCE TO USEC AND THE UNITED STATES

With the retirement of diffusion capacity during the next decade, the artificially high price of enrichment could fall. (It is "artificially" high due to entry barriers: Were there open markets in enrichment, new cheaper capacity would have forced the retirement of diffusion technology much sooner). Entry of new participants into the enrichment market is constrained by non-proliferation considerations, as well as by commercial interests. Enrichment technology is now being more closely guarded with the discovery of a Pakistani enrichment technology smuggling network, which stole centrifuge technology from Urenco in the 1970s, used that technology to develop nuclear weapons in Pakistan, then sold or traded the technology with several other countries, sparking a nuclear arms race with its neighbors and enabling nuclear weapons development in North Korea.

Without market intervention, prices could fall to competitive levels. This implies there might be no economic profit for anyone but the Russians and Europeans. Therefore, the financial outlook for uranium enrichers has been bleak, prompting a Standard and Poor's analyst to write:

> Standard & Poor's Ratings Services affirmed its "A-/A-2" long- and short-term corporate credit ratings on Europe-based uranium enrichment company Urenco Ltd. . . . The enrichment market is undergoing very drastic changes, as TENEX (Rosatom)—which controls roughly 50% of global enrichment capacity but only 24% market share among end-customers—is looking to increase its share of direct sales to end-customers. The extent to which this will affect Western enrichment suppliers—USEC Inc. (B-/Negative/–), Areva (not rated), and Urenco—over the medium term remains to be seen, but will be strongly influenced by ongoing political and trade negotiations . . . The other major industry change is an expected phase-out of the non-economical gaseous diffusion plants used by USEC and Areva . . . (These ratings were re-affirmed on April 24, 2008.)[11]

"A−" implies that Standard & Poor's believes that (1) "economic situation can affect finance" (A) and (2) that the rating is "likely to be downgraded" (−); where A−, BB, BB−, B+, B−, etc., are lower and lower credit ratings for

Table 2: USEC credit ratings report card, 2002–2008.

Standard & Poor's	2002	2003	2004	2005	2006	2007	2008
Corporate credit rating	BB	BB	BB–	B+	B–	B–	B–
Senior unsecured debt	NA	BB-	B	B	CCC	CCC	CCC
Outlook	Negative	Stable	Negative	Negative	Negative	Negative	Negative
Moody's							
Corporate credit rating	Ba1	Ba1	Ba2	B1	B1	B3	B3
Senior unsecured debt	NA	Ba2	Ba3	B2	B3	Caa2	Unrated
Outlook	Negative	Negative	Review	Stable	Review	Negative	Negative

Sources: *USEC Annual Reports* (2002–2007) and *Form 10-K, December 31, 2008* (Feb. 26, 2009).

"non-investment" grade bonds. Since 2002, USEC has been forced to pay high bond rates on its rising debt, while trying to finance a new, First-of-a-Kind technology. This situation has been deteriorating; see Table 2.

Therefore, assuring adequate diversity of enrichment capacity could be problematic without a more comprehensive market intervention (rather than continued subsidization, or not, by national governments). A Russian-European duopoly in enrichment might provide an adequate diversity of supply. But the U.S. Government must determine how many suppliers should be in the enrichment market to maintain market competition or whether any form of market regulation is necessary.

The U.S. Government has been subsidizing the USEC since its privatization; it is unlikely that USEC will survive without a continuous infusion of federal capital until the ACP is finished. If USEC does survive, it might not be competitive enough to grow, if only because USEC has so little experience with operating and manufacturing centrifuge technology. If USEC fails, the U.S. Government could be required to nationalize the American Centrifuge Plant to provide services to defense programs (e.g., naval reactors), as well as pay for decommissioning the gaseous diffusion facilities and all other outstanding USEC liabilities.

On the other hand, American electric utility demand can be supplied by Americans working at the Areva and Urenco plants in Idaho and New Mexico, and by the Russians through the extension of current contracts. Therefore, while it is not in the American electric utilities' interest to support USEC's high prices, it could be in their interest to support the existence of USEC as a hedge against dependence on one or two suppliers.

Unregulated enrichment markets will not necessarily lead to a socially optimal diversity of enrichment suppliers: a long-run equilibrium where the industry is *necessarily concentrated* such that there is no proliferating entry, but is *sufficiently diverse* so that no one national group can dictate prices, contract terms, or non-proliferation policy. United States decision makers should determine (1) whether a Russian-European duopoly is in the United States' national interest, given the dependence of the U.S. nuclear navy on highly enriched uranium (or whether highly enriched uranium stockpiles would be adequate for the foreseeable future), (2) whether to continue to subsidize USEC, or re-nationalize it in the national interest of the United States to facilitate the implementation of non-proliferation policy, and (3) whether some form of enrichment market regulation should be encouraged to assure low-enriched uranium at reasonable prices, particularly for U.S. electric utilities.

NOTES AND REFERENCES

1. G.S. Rothwell, "International Light Water Nuclear Fuel Fabrication Supply: Are Fabrication Services Assured?" *Energy Economics* (2009, in press).

2. G.S. Rothwell, "Market Coordination in the Uranium Oxide Industry," *Antitrust Bulletin* (Spring 1980): 233–68.

3. U.S. Department of Justice and Federal Trade Commission. *Horizontal Merger Guidelines* (1997), Section 1.51, p. 3.

4. B. Cabrera-Palmer, and G.S. Rothwell. "Why is Brazil Enriching Uranium?: To Assure Its Nuclear Fuel Cycle," *Energy Policy* (2008): 2570–2577.

5. In 129 S.Ct. 878 (January 29, 2009) the U.S. Supreme Court reversed a lower federal court decision that enrichment was not a "good," as defined in U.S. anti-dumping law. Still, this paper occasionally refers to enrichment as a "service."

6. Because of the trade-off between uranium and uranium enrichment, the nuclear power plant operator can purchase either less uranium with more SWU, lowering the percentage of Uranium-235 in the tails; or more uranium with less SWU, with an increase in the percentage of Uranium-235 in the tails; See M. Bunn, S. Fetter, J.P. Holdren, and Bob van der Zwaan, *The Economics of Reprocessing vs. Direct Disposal of Spent Nuclear Fuel*. Project on Managing the Atom, Belfer Center for Science and International Affairs, John F. Kennedy School of Government, Harvard University, Cambridge, MA (2003). Referencing the calculation of the optimal tails assay on p. 94, however, the approximation in equation (A.16) fixes the feed assay at 0.711%. Equation (A.16), therefore, cannot be used to determine the optimal re-enrichment of tails or reprocessed uranium.

7. V. Mikhailov, "The Enrichment Industry in the Russian Federation," Uranium Institute Symposium, Russian Ministry for Atomic Energy, Moscow (1995).

8. This assumes that Russia continues to use a lower than optimal tails assay to fulfill fuel contracts by using less Russian uranium, thus increasing "domestic" SWU consumption and reducing SWU on the world market. So, in Figure 3, only one-half of Novouralsk's capacity is competing in the world market.

9. It is difficult to know long-term contract prices, which could be *much lower* than spot market prices, and thus industry profits could be *much lower* than the maximum revenue of $4,500M. However, the industry could still be following the contractual practice of the U.S. Atomic Energy Commission. "Applicable charges for enriching services and related services will be those in effect at the time of delivery of enriched uranium to the customer." U.S. Atomic Energy Commission (AEC). *AEC Gaseous Diffusion Plant Operations*, ORO-684. Washington, DC. 1972, 46. For implications of this policy in the uranium market, see Rothwell, "Market Coordination in the Uranium Oxide Industry."

10. P. Upson, "Centrifuge Technology: the Future for Enrichment," presented at the World Nuclear Association Annual Symposium 2001 (6 September 2001).

11. Standard & Poor's. "Urenco Ltd. 'A-/A-2' Ratings Affirmed Despite More Ambitious Expansion; Outlook Stable." (Sept. 29, 2006).

APPENDIX: A MICROECONOMIC-COST-ENGINEERING MODEL OF URANIUM ENRICHMENT FACILITIES

Paul J.C. Harding, the Managing Director of Urenco (Capenhurst) Ltd. (UCL), describes production at his plant in 2005 (to explain his plant's dependency on non-interruptible power):[1]

- 40% of Urenco's total current enrichment capacity is at UCL
- UCL has 390 employees
- Annual electricity consumption is 180,000 MWh (~ 20MWe continuous demand)
    - Once started, aim is never to stop gas centrifuge machines
    - Need no maintenance
    - Low failure rate
    - Oldest machines at site have run continuously since 1982!
    - If machines are stopped, risk is they will not start again

This Appendix creates a top-down, microeconomic-cost-engineering model to project levelized costs at facilities like Capenhurst. To account for the capital, labor, electricity, and other expenses, let the total annual cost of producing total annual SWU be

$$TC = p_K K + p_L L + p_E E + p_H H, \tag{1}$$

where

- K is the total capital investment cost (TCIC),[2] measured in millions, M, of 2008 dollars, and p_K is the annual capital charge rate (ignoring decommissioning costs);
- L is the number of employees, and p_L is annual (burdened) salary of an employee;
- E is the electricity input MWh, and p_E is the price of electricity in dollars per MWh; and
- H represents the cost of hardware (materials) consumed, and p_H is the price of hardware.

Assume that (1) H is a linear function of K, and (2) p_H is expressed in percent per year of K (e.g., set p_H to the physical depreciation rate). Let $p_{KH} = p_K + p_H$. The Levelized Cost, or Long-Run Average Cost, AC, is

$$AC = \left\{ \sum (p_{KH} K + p_L L_t + p_E E_t)(1+r)^{-t} \right\} \Big/ \left\{ \sum SWU_t (1+r)^{-t} \right\}, \tag{2}$$

where the summation is over the facility's commercial life, all construction costs are discounted to the commercial operation date, and r is the appropriate discount rate. Also, following Harding, there is an implicit assumption of a constant annual capacity factor of 100 percent, because "If machines are stopped, risk is they will not start again."[3] Levelized average cost is calculated assuming all costs and all outputs are equal across time; when this is true, "levelized cost" in cost engineering is equal to "average cost" in microeconomics.

Returns to scale in cost is the ratio of the percentage change in total cost, TC, with respect to a percentage change in output, SWU:[4]

$$\mathrm{RS} = (\Delta TC/TC)/(\Delta SWU/SWU) \approx (dTC/d\,SWU)/(TC/SWU) \qquad (3)$$

For example, if output is increased by 10%, and total cost increases by less than 10%, there are increasing returns to scale, and average costs are falling. If output is increased by 10%, and total cost increases by more than 10%, there are decreasing returns to scale, and average costs are rising. For many production processes, average costs fall with increases in capacity (because average fixed costs are falling). At some capacity range, average costs are constant, but beyond that range, average costs rise with decreasing returns to scale. This yields a U-shaped average cost curve.

However, in industries with increasing returns to scale (where there are large fixed, capital costs), the average cost curve continually declines throughout the relevant range of industry output. This yields a "bath-tub-shaped" average cost curve, where average cost eventually increases at some very large size. This type of cost structure implies that large firms have lower costs than smaller firms. If there is no arrangement to divide the market and profits, the smaller firms could be driven from the industry by retiring capacity (or never entering). At the limit, one large firm could dominate the industry.

The remainder of this Appendix proposes and tests whether there are increasing returns to scale in capital, K, and labor, L, for centrifuge capacity (there is not enough information to estimate returns to scale in energy). With these input prices and estimates of the derivatives of the inputs with respect to changes in facility size, returns to scale in total cost are examined through constructing and analyzing the resulting average cost curves in the last section, Estimating the Long-Run Average Costs of Centrifuge Facilities.

ESTIMATING NEW CENTRIFUGE ENRICHMENT FACILITY COSTS

Estimating New Centrifuge Facility Capital Costs

The price of capital, p_K, is the annual capital charge rate. The model uses a 5 percent *real* cost of capital with capital cost amortization over 30 years, or $p_K = 6.5$ percent.[5] (The real cost of capital is approximately equal to the nominal cost of capital minus the expected inflation rate; with expected inflation at 3 percent, the nominal cost of capital would be about 8 percent, which is appropriate for a regulated utility.) Also, the model assumes the annual *physical* depreciation cost is 1 percent of overnight costs. So, $p_H \ H = 0.01 \ k = 0.01/1.1748 \ K = 0.0085 \ K$). So, $p_{KH} = 6.5\% + 0.85\% = 7.4\%$. (While parameter values are estimated using econometric models, the analysis could also be presented in parametric form; however, it is easier to understand the qualitative conclusions when presented with numeric estimates, even though these might not be the "true" values given the proprietary nature of the cost and technological data.)

The difference between overnight costs (k) and total capital investment costs (K) is the addition of Interest During Construction (IDC) and contingency. IDC discounts construction expenditures to the start of commercial operation. The IDC rate is a function of the expenditure rate, the cost of capital, and construction length. Because centrifuge enrichment facilities can be built in stages, IDC is charged over the lead time of stage construction, assuming a lead time of 3 years per stage. At a cost of capital of 5 percent, IDC adds 7.5 percent to the project's cost. The contingency rate is 10%. So $K = (1 + 0.075 + 0.10) \ k = 1.175 \ k$.[6]

Overnight construction cost, k, for new centrifuge facilities is estimated with information on five facilities in the United States, France, and Brazil:

1. The American Centrifuge Plant (ACP) is being built in Ohio by USEC, using a U.S. DOE-USEC developed centrifuge producing about 300 SWU per year. USEC estimated the first stage will cost $3,500M in 2008 dollars for a capacity of 3.8M SWU. The facility might be completed by 2012.[7]
2. The Urenco New Enrichment Facility (NEF) in New Mexico with a 3M SWU per year capacity is based on Urenco technology (TC-12 machines) with a separative capacity of 50 SWU per centrifuge per year. Construction started in August 2006, with the first set of stages to operate in 2010, and full capacity operation expected in 2013. The overnight cost has been estimated at $1,500M (in 2006 dollars, or $1,650 in 2008 dollars).[8]
3. Areva is building a $2,000M, 3M-SWU-per-year facility in Idaho. Areva expects the ETC centrifuge-supplied facility (TC-12 machines with a capacity of 50 SWU per centrifuge per year) to start operating in 2014, and enter full production in 2019.
4. The new George Besse II enrichment facility, with a capacity of 7.5M SWU per year, near Tricastain, France, is also based on Urenco's TC-12 centrifuges. This facility is being built by Eurodif, a member of the French Areva group. The estimated cost is € 3,000M (2003) (or $3,275M 2003 dollars, or $4,066M 2008 dollars).[9]

5. Brazil is building an enrichment facility at Resende to supply 203,000 SWU by 2015 for its Angra 1 and 2 nuclear power plants. They are using a Brazilian Navy developed centrifuge design that is initially producing about 10 SWU per centrifuge per year. The estimated construction cost is about 541M 2006 Brazilian Real, or about \$278M 2008 dollars.[10]

Before analyzing this information, note that the model is based on three centrifuge technologies at different maturities: The Urenco TC-12 centrifuge has been in commercial operation for more than a decade and can be reproduced at Nth-of-a-Kind cost. The smaller Brazilian centrifuge is in its First-of-a-Kind commercial deployment. The ACP larger centrifuge is being scaled up from prototype to commercial size. Consider the uncertainty in estimating SWU per centrifuge in Guizzo:[11]

> The less technically advanced machines, such as those reportedly used by Iran, each have a capacity of 3 SWU per year. State-of-the-art machines, such as those used by Urenco, are estimated to have a capacity of 50 to 100 SWU. The new American centrifuges are designed to operate at 300 SWU, assuming they will work. Brazil's centrifuges have a capacity of around 10 SWU or a little more, sources familiar with the project told me. These sources, who spoke on condition of anonymity because of the classified nature of the project, say that the machines are nearly 2 meters tall and are supercritical. They add that Brazilian navy researchers are now attempting to increase the length of the rotor without having to redesign its driving and bearing systems. That modification, they say, could improve the machines' performance.

Therefore, these are conditional estimates in this paper that should be revised when more information is publicly available.

Table A.1 gives the descriptive statistics for these data. The variables have been scaled so their means are similar. Here, the minimum value for overnight cost, k, is 0.278 billion 2008 dollars and the maximum value is \$4.066 billion. The minimum value for *SWU* is 0.203 million SWU per year, and the maximum is 7.5 million SWU per year. *RATE* (the centrifuge rating in SWU per year) is given in 100s of SWU per centrifuge, so the minimum value is 0.1 (x 100) SWU per centrifuge for Brazil and the maximum is 3.0 (x 100) SWU per centrifuge

Table A.1: Descriptive statistics of the capital variables.

	Descriptive Statistics				Correlation		
Variables	Mean	Std Dev	Min	Max	*k*	*SWU*	*RATE*
k (\$B)	2.299	1.513	0.278	4.066	1	92%	54%
SWU (M)	3.501	2.620	0.203	7.500	92%	1	17%
RATE (100s)	0.920	1.176	0.100	3.000	54%	17%	1

for ACP. Overnight cost is highly correlated with capacity size, SWU, (92%) and correlated (54%) with output rating, $RATE$; SWU_i, is equal to the number of centrifuges at the plant, $CENTS_i$, times $RATE_i$.[12]

With this information, linear and log-linear models of k are estimated and presented as functions of annual SWU capacity, SWU_i. The linear and log-linear functional forms are presented in Eqs. (4) and (5). However, returns to scale can be directly estimated only from the log-linear form. So, the linear form is presented for completeness; it is not used for hypothesis testing or forecasting. The Ordinary Least Squares (OLS) parameter estimates are[13]

$$k_i = 0.44 + 0.53\,SWU_i \quad (\mathrm{R}^2 = 84\%,\ \mathrm{F\,sig.} = 97\%) \tag{4}$$

$$\ln(k_i) = -0.09 + 0.76\,\ln(SWU_i) \quad (\mathrm{R}^2 = 96\%,\ \mathrm{F\,sig.} = 99\%) \tag{5}$$

The linear form is not as well estimated as the log-linear form. Therefore, Eq. (5) is used for hypothesis testing and forecasting. With the scale factor equal to 0.76 and a standard error of 0.09, there is a greater than 90% confidence that the scale factor is not equal to 1.0, as it would be under constant returns to scale. Therefore, the hypothesis of constant returns to scale can be rejected. The scale factor in Eq. 5 is used to forecast overnight capital costs.

Estimating New Centrifuge Facility Labor Costs

Next, following Cabrera-Palmer,[14] the model uses a “fully burdened” average annual salary of $60,000 in Brazil, based on a base salary of approximately $35,000 per year and a 70 percent burden rate.[15] The model uses a burdened annual salary in France and the United States of $120,000, based on information in the Enrichment Technology Company Limited Annual Report and Accounts for 2006.[16] The model assumes real labor rates have not increased since 2006.

Second, regarding labor, L, the announced projected ACP staff size is 500 employees,[17] the staff size of NEF has been announced to be 210, Areva announced that it would be hiring at least 250 full-time employees at Idaho, and the staff size of Resende is estimated to be 100.[18] Also, while not a new facility, there are 390 employees at Urenco’s Capenhurst facility (producing 3.4M SWU per year); this provides a benchmark and another observation.

Because one observation is different from one in Table A.1, Table A.2 provides the descriptive statistics and correlations for the labor data set. The variables have been scaled so their means are similar. In Table A.2 the minimum value for the number of employees, L, is 1.0 (x 100) employees, and

Table A.2: Descriptive statistics of the labor variables.

	Descriptive Statistics				Correlation		
Variables	Mean	Std Dev	Min	Max	*L*	*SWU*	*RATE*
L (100s)	2.900	1.567	1.000	5.000	1	83%	82%
SWU (M)	2.681	1.424	0.203	3.800	83%	1	57%
RATE (100s)	0.920	1.176	0.100	3.000	82%	57%	1

the maximum is 5 (x 100) employees. The maximum SWU is less than in Table A.1 because labor data could not be found for George Besse II. The number of employees is highly correlated (82–83%) with the both the number of SWU and with the *RATE*; *SWU* and *RATE* are positively correlated (57%).

With this information, linear and log-linear models of L (staff size) are estimated and presented as functions of annual SWU capacity:

$$L_i = 0.46 + 0.91 SWUi \quad (\mathrm{R}^2 = 68.6\%,\ \mathrm{F\,sig.} = 91.7\%) \tag{6}$$

$$\ln(L_i) = 0.65 + 0.43\ \ln(\mathrm{SWU}i) \quad (\mathrm{R}^2 = 76.0\%,\ \mathrm{F\,sig.} = 94.6\%) \tag{7}$$

The linear form is not as well estimated as the log-linear form. Equation (7) is used for hypothesis testing and forecasting. With the scale factor equal to 0.43, and a standard error of 0.14, there is a 98 percent confidence in rejecting constant returns. So, one can also conclude there are increasing returns to scale in labor, as with capital. Equation (7) is used to forecast labor, L.

Estimating New Centrifuge Facility Energy Costs

Third, the electricity consumption for ETC and ACP centrifuges are from the World Nuclear Association:[19] 50 kWh/SWU to run the centrifuges, and 62.3 kWh/SWU to run the plant. The electricity consumption for Resende centrifuges is from Cabrera-Palmer and Rothwell: 100 kWh/SWU.[20] Further, following Cabrera-Palmer and Rothwell, and updating the price to 2008 dollars, let the delivered price of electricity be \$106.72/MWh (or \$0.107/kWh), which includes transmission and distribution fees.[21] Because electricity generation is about one-half of total costs, the generation cost is approximately \$53.36/MWh or \$0.053/kWh.

Estimates of New Centrifuge Facility Costs

Table A.3 presents the estimated levelized cost per SWU for new centrifuge facilities assuming a real 5 percent cost of capital. The capital intensity of centrifuge enrichment technology yields an annual capital charge that is 2/3rds of

Table A.3: Levelized SWU costs, future centrifuge capacity (5% cost of capital, 6.51% capital recovery factor, +7.48% IDC, 10% contingency).

Firm Plant	(2008$)	USEC ACP	Urenco NEF	Areva Idaho	Eurodif Besse II	Brazil Resende
Plant capacity	t SWU/yr	**3,800**	**3,000**	**3,000**	**7,500**	**203**
Overnight cost	$M	$3,500	$1,650	$2,000	$4,066	$278
Total capital invest cost	$M	$4,152	$1,957	$2,372	$4,823	$330
Capital/SWU	$/SWU	**$71.07**	**$42.44**	**$51.44**	**$41.83**	**$105.68**
Staff size	people	500	210	250	481	100
Annual fully burden salary	$k/yr	$120	$120	$120	$120	$60
Labor/SWU	$/SWU	**$15.79**	**$8.40**	**$10.00**	**$7.70**	**$29.56**
Electricity consumption	kWh/SWU	62	62	62	62	100
Electricity price	$/MWh	$107	$107	$107	$107	$107
Electricity/SWU	$/SWU	**$6.65**	**$6.65**	**$6.65**	**$6.65**	**$10.67**
Materials/SWU	$/SWU	**$9.21**	**$5.50**	**$6.67**	**$5.42**	**$13.69**
Annual total costs	$M	**$390**	**$189**	**$224**	**$462**	**$32**
Levelized SWU cost	$/SWU	**$103**	**$63**	**$75**	**$62**	**$160**

total annual cost. Labor is about 1/6th of total costs, and electricity and hardware make up the remaining 1/6th. Table A.3 shows

- The Urenco technology facilities (NEF in New Mexico and George Besse II in France) will likely have lower costs than the USEC's ACP.
- The levelized cost of Brazil's small facility could be twice as high as the cost at the ACP, and almost three times as much as average cost at the Urenco facilities.

PROJECTING REPLACEMENT COSTS OF OPERATING CENTRIFUGE FACILITIES

This section approximates the cost structure of the existing commercial centrifuge facilities owned by Urenco, JNFL, and Rosatom. See Table A.4 and Table A.5. Urenco has three production facilities at Capenhurst, United Kingdom, with 3.4M SWU; Almelo, Netherlands, with 2.9M SWU; and Gronau, Germany, with 1.8M SWU. The overnight replacement costs (in 2008 dollars) are estimated using Eq. (5). Because these facilities have already been built and some of the capital has been depreciated, there is no contingency or IDC, so total capital investment cost (K) is equal to the estimated overnight replacement cost (k). (This assumption reduces the levelized capital costs at older facilities by about 10 percent.) Here, Urenco and JNFL use a real cost of capital of 5 percent. The Urenco facilities yield levelized costs in the same range as the new facilities in the United States. Costs at Rokkasho, Japan, are higher due to its small size (also Japanese levelized costs could be even higher due to low

Table A.4: Levelized SWU costs, operating centrifuge capacity (Europe and Japan) (5% cost of capital, 6.51% capital recovery factor, +0% IDC, 0% contingency).

Firm Plant	(2008$)	Urenco Capenhurst	Urenco Almelo	Urenco Gronau	JNFL Rokkasho
Plant capacity	t SWU/yr	**3,400**	**2,900**	**1,800**	**1,500**
Overnight cost	$M	$2,342	$2,076	$1,445	$1,095
Total capital invest cost	$M	$2,342	$2,076	$1,445	$1,095
Capital/SWU	$/SWU	**$44.82**	**$46.56**	**$52.21**	**$56.98**
Staff size	people	340	317	257	219
Annual fully burden salary	$k/yr	$120	$120	$120	$120
Labor/SWU	$/SWU	**$11.99**	**$13.10**	**$17.12**	**$20.99**
Electricity consumption	kWh/SWU	62	62	62	62
Electricity price	$/MWh	$107	$107	$107	$107
Electricity/SWU	$/SWU	**$6.65**	**$6.65**	**$6.65**	**$6.65**
Materials/SWU	$/SWU	**$6.89**	**$7.16**	**$8.03**	**$8.76**
Annual total costs	$M	**$239**	**$213**	**$151**	**$117**
Levelized SWU cost	$/SWU	**$70**	**$73**	**$84**	**$93**

capacity factors at Rokkasho; and as its capacity factor declines, its average costs could become the world's highest.)

The same analysis is applied to estimate the costs at Rosatom's centrifuge facilities in Novouralsk (UEKhK, Sverdlovsk Oblast) with 12.45M SWU, Zelenogorsk (EKhZ, Krasnoyarsk Kray) with 7.39M SWU, Seversk (SKhK, Tomsk Oblast) with 3.65M SWU, and Angarsk (Irkutsk Oblast) with 2.5M SWU.[22] Again, the replacement values of the facilities can be modeled with Eq. (5) and labor requirements with Eq. (7). In determining appropriate parameter values, consider Bukharin:[23]

Table A.5: Levelized SWU costs, existing centrifuge capacity (Russia) (2.5% cost of capital, 4.78% capital recovery factor, +0% IDC, 0% contingency).

Firm Plant	(2008$)	Tenex UEKhK	Tenex EKhZ	Tenex SKhK	Tenex Angarsk
Plant capacity	t SWU/yr	**12,450**	**7,390**	**3,650**	**2,500**
Overnight cost	$M	$6,282	$4,226	$2,472	$1,854
Total capital invest cost	$M	$6,282	$4,226	$2,472	$1,854
Capital/SWU	$/SWU	**$24.11**	**$27.32**	**$32.36**	**$35.44**
Staff size	people	601	478	350	297
Annual fully burden salary	$k/yr	$60	$60	$60	$60
Labor/SWU	$/SWU	**$2.90**	**$3.88**	**$5.76**	**$7.12**
Electricity consumption	kWh/SWU	62	62	62	62
Electricity price	$/MWh	$53	$53	$53	$53
Electricity/SWU	$/SWU	**$3.32**	**$3.32**	**$3.32**	**$3.32**
Materials/SWU	$/SWU	**$5.05**	**$5.72**	**$6.77**	**$7.42**
Annual total costs	$M	**$440**	**$297**	**$176**	**$133**
Levelized SWU cost	$/SWU	**$35**	**$40**	**$48**	**$53**

> Large separative capacities and low production cost—possibly on the order of \$20 per SWU (compared to approximately \$70 per SWU in the United States)—which is made possible by the use of highly-efficient centrifuge technology, and access to low-cost electricity, materials and labor, make the Russian enrichment enterprise highly competitive.

Therefore, assume for Russian plants that (1) the real cost of capital is 2.5%, leading to a capital recovery factor of 4.8% (versus 6.5% for the other centrifuge facilities), (2) the burdened cost of labor is \$60,000 equal to that in Brazil, and (3) the cost of electricity of \$53/MWh (implicitly assuming that the cost of transmission and distribution is zero). See Table A.5. The estimated levelized cost in 2008 dollars is between \$35 for the largest facility and \$53 for the smallest facility, lower than at all other enrichment facilities. Bukharin's ratio of \$20 to \$70 is identical to the ratio of a weighted average of Russian prices of \$46 to late-2008 spot-market prices of \$160/SWU. The Russian enrichment enterprise continues to remain highly competitive.

PROJECTING COSTS OF THE DIFFUSION FACILITIES

Finally, the model is used to approximate the cost structure of the existing commercial diffusion plants owned by USEC and Eurodif. See Table A.6. Of course, this is a different technology (however, nearly 85 percent of the cost of diffusion enrichment is determined by the cost of electricity, so all other costs, approximated with the model of centrifuge technology, are of second order importance). Using the same technique for projecting investment costs as above, the current investment costs (*replacement value*) for each diffusion plant is about \$4,000 M. The model assumes a real 2.5 percent cost of capital to determine the annual capital charge. Assume that Eurodif's newer diffusion plant (completed in 1982) operates at 2,200 kWh/SWU, whereas the older USEC plant (Paducah, completed in 1954) operates at 2,500 kWh/SWU. Because of the size of these facilities, assume dedicated electricity generators at \$53/MWh (again, implicitly, the transmission and distribution costs are zero). This high use of electricity makes the gaseous diffusion plants the highest cost producers in the enrichment industry (with almost half the world's commercially-available capacity). These plants are scheduled to retire in the next decade.

ESTIMATING THE LONG-RUN AVERAGE COSTS OF CENTRIFUGE FACILITIES

A reciprocal functional form is used to estimate the relationship between average cost, *AC*, and size, *SWU*, in these simulated data:

$$AC = \gamma + \delta(1/SWU). \tag{8}$$

Table A.6: Levelized SWU costs, existing diffusion capacity (U.S. and France) (2.5% cost of capital, 4.78% Capital Recovery Factor, +0% IDC, 0% Contingency)

Firm Plant	(2008$)	USEC Paducah	Areva Eurodif
Plant capacity	t SWU/yr	8,000	11,300
Overnight cost	$M	$4,488	$5,836
Total capital invest cost	$M	$4,488	$5,836
Capital/SWU	$/SWU	$**18.98**	$**25.82**
Staff size	people	495	576
Annual fully burden salary	$k/yr	$120	$120
Labor/SWU	$/SWU	$**6.88**	$**8.61**
Electricity consumption	kWh/SWU	2,500	2,200
Electricity price	$/MWh	$53	$53
Electricity/SWU	$/SWU	$**133.38**	$**117.37**
Materials/SWU	$/SWU	$**3.97**	$**5.40**
Annual total costs	$M	$**1,826**	$**1,674**
Levelized SWU cost	$/SWU	$**163**	$**157**

Average cost is calculated for *hypothetical* plants of many sizes at real costs of capital of 5% and 10%. The relationship between average costs and the reciprocal of size is estimated using OLS. Figure A.1 represents these relationships, where the OLS results are shown on the figure. (Here, increasing returns to scale are nearly exhausted at the "Minimum Efficient Scale" (MES) between 2.5 and 2.9 million SWU, which is where costs are not more that 10 percent of the asymptote, equal to the constant, γ.) As an example, for a plant with a capacity of 1 million SWU per year with $r = 10\%$, the

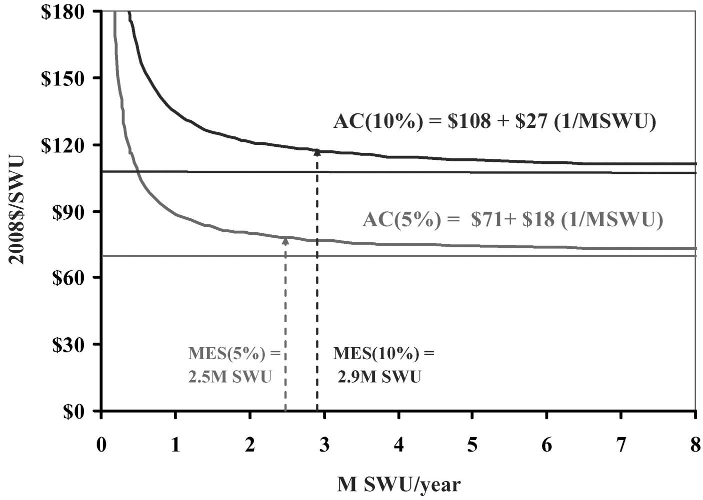

Figure A.1: Estimated cost curves, centrifuge technology.

levelized average cost would be approximately \$108 + \$27 = \$135/SWU in 2008 dollars.

Here, it is unknown where the average cost curve, as portrayed in Figure A.1., might begin to increase. Given that Russia could have increased capacity in any of their facilities, and yet capacity at Novouralsk (UEKhK) has been increased to at least 12.45 M SWU per year, it is reasonable to conclude that costs are not yet increasing at UEKhK. So it is unlikely that average costs at a generic centrifuge facility begin to increase before 12 M SWU per year, which is four times the size of any plants being built in the United States, and is off the graph in Figure A.1.

NOTES AND REFERENCES FOR APPENDIX A

1. Paul Harding, "The Role of U.K. Business in Providing Security of Energy Supply from Nuclear Power," presented at British Energy Association Workshop, London (14 April 2005).

2. Economic Modeling Working Group (EMWG). *Cost Estimating Guidelines for Generation IV Nuclear Energy Systems*. (EMWG of the Generation IV International Forum, 2007).

3. Paul Harding, op. cit.

4. G.S. Rothwell, and T. Gomez. *Electricity Economics: Regulation and Deregulation* (IEEE Press/John Wiley, 2003).

5. B. Cabrera-Palmer, and G.S. Rothwell, op. cit.; Economic Modeling Working Group (EMWG). *op. cit.*

6. Economic Modeling Working Group (EMWG), op. cit.

7. USEC. "Remarks by John K. Welch, President and Chief Executive Officer at the Annual Shareholders' Meeting of USEC Inc." Bethesda, MD (April 26, 2007).

8. WNA (World Nuclear Association). "Uranium Enrichment."

9. WNA (World Nuclear Association), op. cit.; Autebert, R. (representing AREVA). "Feeding the Nuclear Fuel Cycle with a Long Term View—AREVA's Investments in Front End Activities," presentation at the World Nuclear Fuel Market (WNFM) Annual Meeting, Seattle, WA (6 June 2006).

10. B. Cabrera-Palmer, and G.S. Rothwell, op. cit.

11. E. Guizzo, "How Brazil Spun the Atom," IEEE Spectrum (March 2006), 6.

12. All OLS estimates were also done with *CENTSi* as an explanatory variable. It was not statistically significant in any equation by itself or with other variables. *RATEi* was also used as an independent variable in all statistical analyses to determine the robustness of the coefficient estimates on *SWUi*. These results are available from the author.

13. Several functional forms were estimated, including semi-log, reciprocal, and log-reciprocal. The linear, log-linear, and log-reciprocal models had the highest explanatory power, and no model yielded decreasing returns to scale. This was also true for

Equations (6) and (7). See, J. Johnston and J. Dinardo. *Econometric Methods*, 4th ed. (McGraw-Hill, 1997), 44.

14. B. Cabrera-Palmer and G.S. Rothwell, op. cit.

15. Economic Modeling Working Group (EMWG), op. cit.

16. Enrichment Technology Company Limited (ETC). *Annual Report and Accounts for 2006* (2007).

17. USEC. "USEC to Site American Centrifuge Plant in Piketon, Ohio," USEC Press Release (2004).

18. B. Cabrera-Palmer and G.S. Rothwell, op. cit.

19. WNA (World Nuclear Association), op. cit.

20. B. Cabrera-Palmer and G.S. Rothwell, op. cit.

21. Ibid.

22. International Panel on Fissile Materials. 2007. *Global Fissile Material Report 2007*. Carnegie Endowment.

23. Bukharin, O. "Understanding Russia's Uranium Enrichment Complex," *Science and Global Security* 12 (2004): 193–218.