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Dynamic Relationships Between Uranium and SWU Prices: A New Equilibrium

Introduction

At the Plenary Session of this meeting in 2004, I analyzed long-term historical trends in the uranium market and forecast rapid increases in prices, based on historical analysis of prices needed to ramp up primary production as secondary inventories were depleted. These price increases subsequently occurred and are rather precisely tracking the increases that occurred in the 1940s and 1970s. In 2004, I also evaluated the combinations of uranium and enrichment supply that could, in principle, meet western demand, pointing out that substitution of enrichment for uranium, by reducing tails assays, would be limited by SWU capacity constraints.

Today, I would like to explore further the dynamic relationship between uranium and enrichment markets, with a particular focus on the relationship between prices in these markets. It is important to note that this exercise is theoretical in nature, in keeping with the nature of WNA discussions. There are many practical constraints, such as legacy contracts and other factors that will affect the precise course of market evolution.

It is usually the case that a rise in the price of one input to a production process-the making of nuclear fuel-should result in an increase in price for another input which is a substitute for it. Indeed, an increase in uranium price results in an increase in demand for enrichment, which can substitute for uranium by reducing tails assay in enrichment. Increased demand and limited capacity should thus result in an increase in the price for enrichment services.

My primary purpose today is to estimate coming changes in enrichment pricing as utilities seek to minimize the cost of nuclear fuel, within supply constraints. In effect, enrichment prices should rise until utilities are neutral about whether to buy more enrichment or more uranium. This is what I call a new equilibrium between uranium and enrichment prices. As we shall see, this evolution is likely to be difficult due to constraints on supply availability over the next decade or so, and due to legacy contracts that inhibit efficient allocation of uranium and enrichment supply.

How History Set the Stage for Problems

For a period of nearly twenty years uranium prices remained low, a result largely of liquidation of commercial and government inventories. As a result, many decisions were made about enrichment that depended on assumptions about uranium prices.

Enrichment contracts reflected assumptions about tails assays remaining in the range of 0.30% to 0.35%. Low uranium prices, and thus low demand for enrichment, led to low enrichment prices. Enrichment companies also made capacity additions, and even designed enrichment plants, based on an assumption about tails assays remaining high, and continued low demand for enrichment. USEC shut down the Portsmouth enrichment plant and plans to replace the Paducah plant with a smaller plant. Areva similarly is replacing its gaseous diffusion plant with a smaller plant.

Enrichers' historical plant additions, and even plans for new enrichment facilities, seem to reflect assumptions about high tails assays and low SWU demand. Ironically, many legacy enrichment contracts allow customers to nominate much lower tails assays and deliver less uranium than was assumed in capacity and design decisions.

Just as people were myopic about uranium supply and prices, so were they myopic about enrichment supply and prices.

The effect of this myopia is visible in enrichment contracts as well as in decisions about capacity. Intense competition in an era of low enrichment demand led to fixed or capped prices in long-term enrichment contracts, the same mistake as was made in uranium contracts. These low prices undermined incentives to expand capacity and even the financial viability of primary suppliers. Their duration in existing contracts continues to do so. In uranium, this has contributed to a shortfall in production capacity. As we will see below, this is also the case for enrichment.

Dynamic Relationship between Uranium and Enrichment Prices

For given SWU and uranium prices there is an optimal tails assay that minimizes the cost of nuclear fuel. This is usually expressed in the form of a graph that plots the ratio of uranium to SWU prices against the optimal tails assay, as in *Figure 1*. A high ratio of uranium to SWU prices results in a cost-minimizing optimal tails assay that is low, currently about 0.22% tails (using spot or new term contract prices).

For the past two decades, low uranium prices resulted in the optimal tails assay being considerably higher. We plot on *Figure 1* the extreme decline in optimal tails since October 2000. If utilities were to operate at optimal tails, SWU requirements would increase by 32%, while uranium requirements would decline by 28%, relative to 2000 figures. In the short term, embedded prices in legacy contracts inhibit this adjustment, but it will have to come.

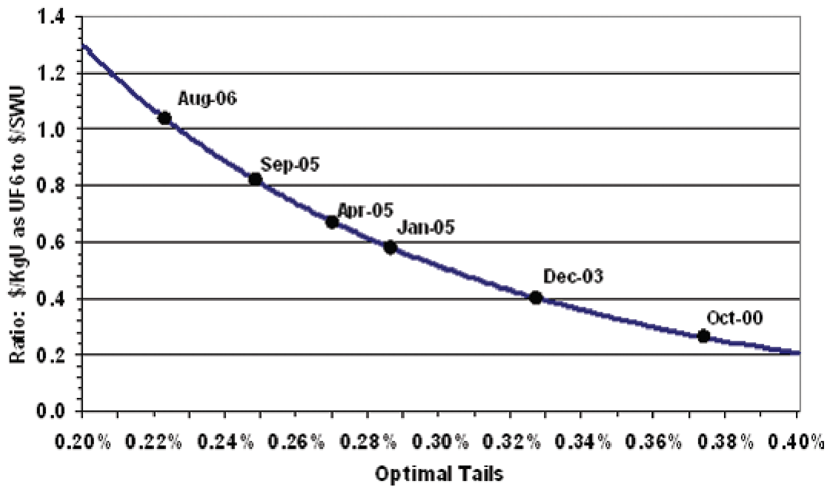

Figure 1: Optimal Tails as a Function of Ratio of Uranium and SWU Prices

SWU price at a given uranium price that minimizes fuel cost at the tails assay shown on the horizontal axis.

For example, *Figure 1* shows that when enrichment was US$100/SWU and uranium was only US$30/kgU, US$100 SWU yielded an optimal tails assay of more than 0.35%. But with uranium price rising to nearly US$140/kgU, US$100/SWU would yield an optimal tails of only 0.20%. That is, there should be massive substitution of enrichment for uranium with SWU price at this level. However, as an economic proposition, enrichment prices should rise to reflect the increased demand for SWU to make this substitution, resulting in a tails assay somewhere between 0.20% and 0.35%.

The conventional approach of *Figure 1* is useful in making short-term decisions about tails assays, but not very useful when it comes to looking at the longer-term dynamic relationships between prices, which is our objective here. We thus recast the relationship between SWU and uranium prices in a different way.

To do this, we ask: Given a specific uranium price, what would SWU price have to be at a given tails assay to make that tails assay economically optimum? Alternatively, given a tails assay and a uranium price, how much could enrichers charge for SWU before utilities would buy and feed more uranium? Finally, if there is a global limit on SWU supply, how high must SWU prices be (for a given uranium price) to clear the market. That is, how much might enrichers charge to allocate SWU capacity efficiently to meet world requirements?

Figure 2 illustrates one way to answer these questions. Each curve represents a uranium price, in dollars per kilogram U as UF6. As of this writing, the spot price is about US$135/kgU. In much of the past two decades it has been more on the order of US$30/kgU. SWU price is shown on the vertical axis and each point on the curve represents a SWU price at a given uranium price that minimizes fuel cost at the tails assay shown on the horizontal axis.

In the short run, embedded prices in enrichment contracts inhibit adjustment in SWU prices, except in new contracts and on the spot market. The same is true for uranium prices, where embedded prices in legacy contracts prevent economic adjustment to new realities of scarcity. Contractual rigidities have two potentially disastrous effects: they prevent efficient allocation of uranium and enrichment resources, and they set the stage for a much more disruptive adjustment later.

To see this, let us suppose that limited enrichment capacity only allows tails assay to be reduced to a certain level, say 0.27% on average (this is the WNA 2005 assumption for western reactors). Let us further suppose that uranium prices stabilize at US$140/kgU. Looking at the *Figure 2*, we see that enrichment suppliers without contract constraints could raise prices to about US$210/SWU before utilities would buy more uranium to raise tails assay to avoid the increased cost (of course, this assumes that such uranium is available). If the minimum achievable tails assay were 0.35% (e.g., due to limited uranium supply), enrichers could raise price to more than US$400/SWU before it would pay to substitute more uranium for enrichment, at the assumed uranium price. Conversely, if there is enough SWU available to operate at 0.20% tails assay, but uranium price remains at US$140/kgU, SWU price could be as low as US$110/SWU.

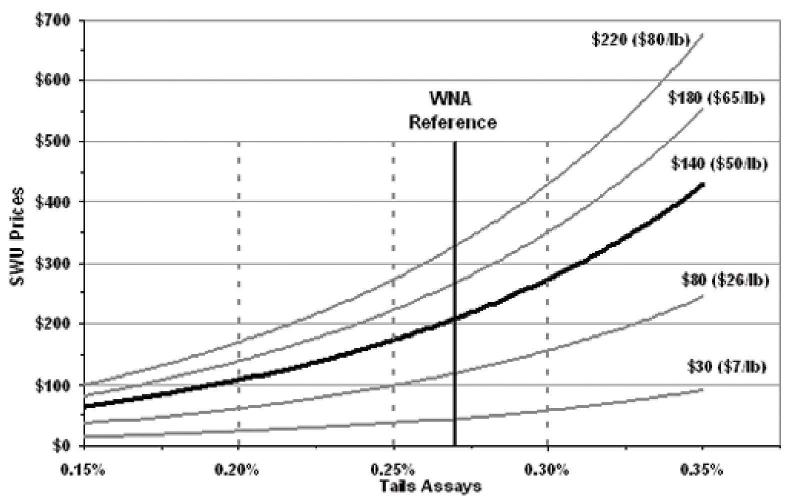

Figure 2: SWU Price at "Optimal" Tails Assays As a Function of Uranium Price ($/KgU as UF6)

Note that if uranium price continues to rise, enrichment suppliers could charge even more for services, at a given tails assay, because the value of SWU to replace uranium also goes up. For example, if uranium is US$180/kgU, enrichers might be able to raise prices to more than $250/SWU at 0.27% tails.

In reality, both uranium and SWU prices, and

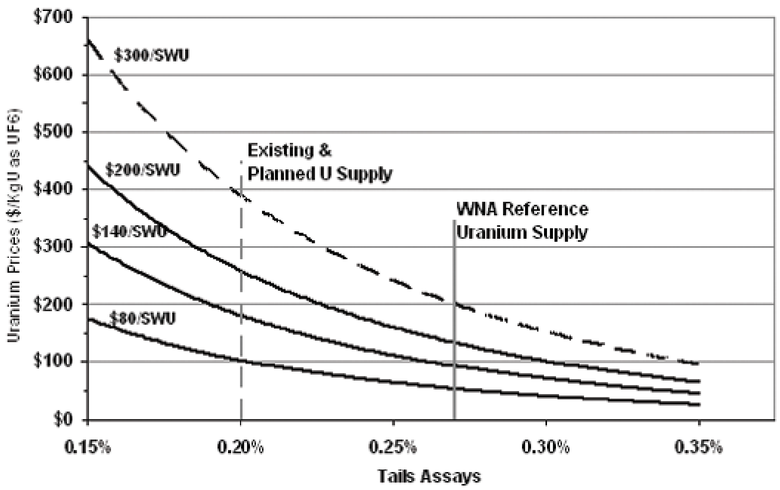

Figure 3: Uranium Price at "Optimal" Tails Assays As a Function of SWU Price

Supply Includes Secondary Supply (WNA: 6,664 tU-equivalent; E & P: 5400 tU-equivalent)

tails assay, will adjust to satisfy demand: our analysis shows how large the economic forces might be to make this happen. In the world of the past two decades, neither SWU nor uranium prices were very high and utilities could focus on other contract terms without losing much on fuel cost optimization. In the new world, there are potentially large economic consequences that will force changes in the supply system.

The above analysis is particularly of interest to SWU suppliers. One might wonder whether one can reverse the above analysis: take SWU price as a given and see what uranium prices must be in the longer term to reach an equilibrium that minimizes fuel cost. *Figure 3* shows the results of such an analysis.

In *Figure 3*, we assume that enrichment supply works its way out to a competitively-determined price, without regard to uranium price. For example, this would be the case if there were more than adequate SWU supply (e.g., from Russia or other sources). For a specific SWU price, we then ask how high uranium prices might be and still make a given tails assay the optimum to minimize fuel cost. Alternatively, how much could uranium suppliers charge before utilities would buy less uranium and use more SWU?

Uranium and SWU prices are thus very strongly interdependent and there are major forces in play to readjust both.

Over longer periods of time-we look at the 2015 time-frame-legacy contracts will expire and a new equilibrium of interdependent uranium and SWU prices will have to be reached. To explore this question, we look at supply and demand for uranium and enrichment in the 2015 period.

Supply and Demand for Enrichment and Uranium

In my 2004 paper, I showed how to look simultaneously at uranium and enrichment demand. *Figure 4* updates that work to take into account the estimates of the 2005 WNA Market Report. In that report, the WNA working group estimated demand using a 0.27% tails assay for "Western" reactors and a 0.10% tails assay for "Russian" reactors in its Reference Case.

Because it is difficult to combine these very different regional systems in a single analysis, and because these systems operate quite differently, I have chosen here to look only at "Western" supply and demand, and to treat the other group as an importer or exporter.

Figure 4 shows alternative combinations of uranium and SWU that will equally well satisfy Western reactor requirements in 2015; that is, they all produce the same amount of EUP (4,000tU for natural uranium reactors is included in uranium requirements). For reactors using enriched uranium, the total is about 6740t EUP at an average final assay of about 4.35%. This (along with natural uranium and secondary supplies) fuels the Western reactor capacity projected by the WNA Reference Scenario for 2015. Requirements in this case are only about 11% above those today, with most of the increase in Asia. Given the high interest in new reactors, this forecast may indeed be low.

Given the number of combinations of enrichment and uranium supply that might meet requirements, we need to look at what supply might be available to see if supply limits the possible combinations. It is not my intent here to make independent forecasts of uranium and enrichment supply but rather to look at current plans and possibilities.

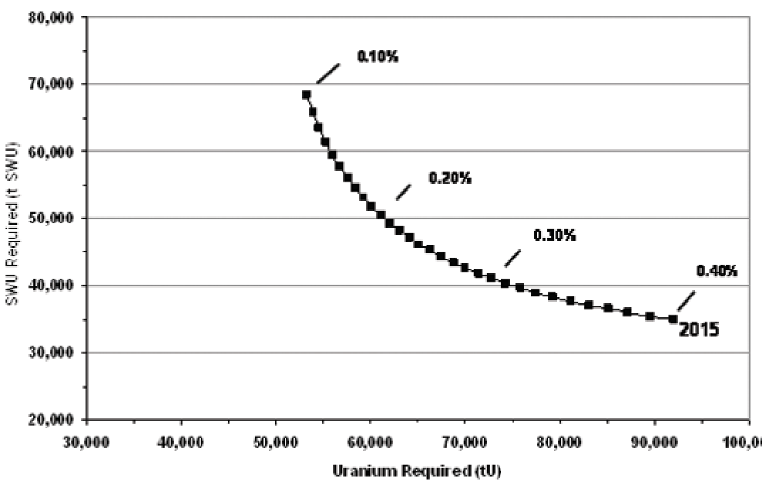

Figure 4: Western Reactor Uranium and SWU Requirements 2015
WNA Reference Scenario

Table 1: ENRICHMENT CAPACITIES: PLANNED AND POTENTIAL FOR 2015

Facility	Planned Capacity	Potential Additional	Total
Urenco	11	4	15
GBII (Areva)	7.5	-	7.5
NEF	3.0	3.0	6.0
USEC	3.5	3.5	7.0
Other	2.8	-	2.8
MOX	1.0	1.0	2.0
TOTALS	28.8	11.5	40.3

Enrichment Supply

Table 1 shows planned western enrichment facilities and possible additions to capacity by 2015. Urenco has announced plans to reach 11 million SWU by 2010; I assume the company could add an additional 4 million SWU of capacity by 2015. Areva expects to reach 7.5 million SWU sometime between 2009 and 2018; I assume this is reached by 2015. NEF in New Mexico is targeting 3 million SWU; I assume up to 6 million by 2015. We also assume that USEC can deploy 3.5 million SWU before 2015, with an additional 3.5 million possible. The "Other" category includes China, Japan and Brazil. Finally, we assume that MOX can provide the equivalent of up to 2 million SWU. I regard most of these estimates as optimistic. Note that there is uncertainty about being able to reach even the Planned Capacity: technical, legal, manufacturing, or operational problems could interfere. The Potential Additional Capacity requires additional licensing and investment, and decisions very soon.

We can now put this range of supply on our graph from *Figure 3*. With only Planned Capacity installed by 2015, Western requirements could not be met, at any tails assay, without substantial additional supply from Russia or continued operation of gaseous diffusion plants. If one adds in Potential Additional Capacity, Western tails assay could only be as low as 0.31% on average. As discussed below, this would require substantially more uranium than is likely to be available. *Figure 5* shows the band of western enrichment supply relative to requirements.

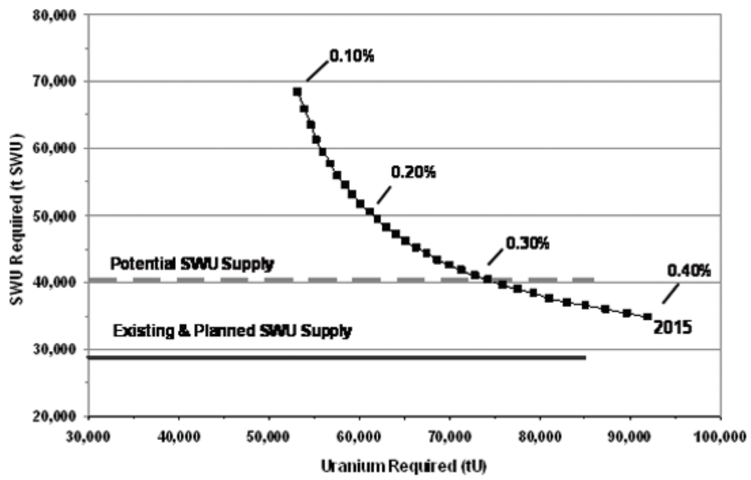

Figure 5: Western Reactor Requirements and SWU Supply

Uranium Supply

Uranium production levels in 2015 are as uncertain as those for enrichment. While there are literally more than a hundred new junior uranium companies and while established producers are seeking to expand output, the amount of production that can be added between now and 2015 is limited by quite a number of factors. First, it is unlikely that a uranium deposit that is not yet found and fully delineated can be in production by 2015. Second, there are very real constraints from the approval and licensing process and from lack of infrastructure, mills, and human capital.

Western uranium production in 2005 was only about 37,000tU. The WNA has three scenarios for supply for Western reactors: the Lower Scenario foresees about 49,000tU in 2015 (about 4,200tU-equivalent from secondary sources); the Reference Scenario projects about 70,000tU-equivalent (about 6,700tU-equivalent from secondary sources) in 2015 and; the Upper Scenario projects about 80,600 tU (about 14,500tU-equivalent from secondary sources). The increase from Reference to Upper scenarios comes largely from an assumed increased secondary supply.

Table 2 lists the specific production and secondary supply assumptions for the WNA Lower and Reference cases. *Table 2* also lists existing and planned uranium production capacity-mines which actually exist or for which specific plans have been made.

The WNA Reference supply case makes critical assumptions about several countries, adding "prospective" capacity to "planned" capacity. For example, in Australia it assumes that Jabiluka (4,500tU) comes into production. In the case of Kazakhstan, it assumes that production reaches 13,719tU/annum, with 2,000tU of this going to Russia. Aflease is assumed to add "prospective" production in South Africa by 2015.

Table 2: URANIUM SUPPLY FOR WESTERN REACTORS IN 2015 (Tonnes U)

	WNA Lower	WNA Reference	Existing & Planned Capacity
Australia	9,202	17,702	13,800
Canada	15,167	16,567	15,380
Kazakhstan	9,219	11,219	8,000
Namibia	1,000	4,038	4,850
Niger	3,282	3,282	3,500
South Africa	755	2,295	2,000
USA	2,738	3,328	3,260
Uzbekistan	2,016	2,516	2,500
Other	1,415	2,265	1,800
Total Primary Supply	44,794	63,212	55,090
Tails Re-Enrichment	1,500	2,500	
Ex-Military MOX	400	400	
MOX + RepU	2,264	2,264	
U.S. DOE Sales	0	1,500	
Secondary Supply	4,164	6,664	5400
TOTAL SUPPLY	48,958	69,876	60,490

These assumptions add more than 8,000tU/annum to existing and planned production. WNA also assumes that planned and potential mines operate at 100% of nameplate capacity, where historical experience indicates a figure closer to 90%.

A large component of supply in the Reference case comes from secondary sources, some of which is problematic. Russia has indicated that it no longer wants to re-enrich tails; the disposition of ex-military plutonium is still being debated; and government sales are highly speculative.

WNA does not characterize its production figures as "a full production forecast" but rather as "an estimate of what is possible." I regard the WNA Reference case for uranium supply in 2015 as optimistic.

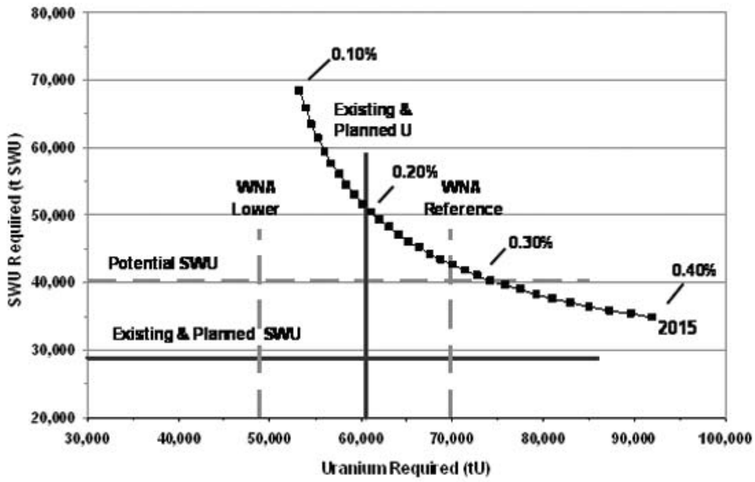

Figure 6: Western Reactor Requirements Compared to Western Supply of Uranium and SWU

We can now add uranium supply estimates to our *Figure 5*, combining them with our estimates for planned and potential western SWU supply. This is shown in *Figure 6*.

As we can see from *Figure 6*, the WNA Reference case for uranium supply does indeed barely meet Western Reference requirements at a tails assay of 0.27%. More conservative uranium estimates, such as existing and planned capacity (also shown), would fall short at this tails assay. However, even in the optimistic case for uranium, planned western supply of enrichment falls far short of what is needed to enrich at or below the 0.27% tails level. If Western enrichers follow their current plans (building only what is being planned and licensed, and shutting down gaseous diffusion), there would be a shortfall of more than 13 million SWU in 2015.

If uranium supply is more limited than the WNA reference case in 2015, say to the 60,490tU shown in our Existing and Planned Capacity column of *Table 2*, tails assay could not be higher than 0.20%. We would need substantially more SWU supply, a total of about 51 million SWU. This is about 22 million SWU more than Western Planned Capacity for enrichment (including secondary supply).

The net result of conservative assumptions about expansion of western production of uranium and enrichment is a need for substantial quantities of both uranium and enrichment, given what increasingly seems a modest forecast of future fuel requirements.

Uranium and Enrichment Pricing

The underlying problem for both uranium and enrichment is tight supply, if not shortage. As a result, suppliers (whether Western or Russian) will have significant pricing power. The central questions are then:

- How much supply of uranium and enrichment services will be available to western buyers; and
- If one or both are scarce, how will the fuel supply system allocate "scarcity rents" between uranium and enrichment suppliers?

We have chosen to cast this problem in terms of tails assay, assuming that, over the longer term, utilities will seek to minimize fuel costs by adjusting tails assays, within the constraints of available supply. The final optimum average tails assay will be determined by the relative success of uranium and enrichment suppliers in capturing scarcity rents.

The above analysis shows that at a given tails assay and uranium price, enrichers can raise price to the point at which utilities seek to increase tails assays by buying more uranium. But buying more uranium drives up the price of uranium. Alternatively, if uranium suppliers increase prices until utilities begin to substitute SWU for uranium at lower tails assay, enrichment suppliers can increase prices. In the past, uranium suppliers and enrichment suppliers competed in over-supplying the market. This is unlikely to happen now.

At the WNA Western tails assay of 0.27%, and with uranium prices at US$140/kgU, enrichers could eventually increase SWU price to about US$210/SWU (see *Figure 2*). If uranium prices rise further, so too could SWU price. The WNA analysis, in effect, maximizes uranium supply and minimizes SWU demand. Even so, there is considerable bargaining leverage for SWU suppliers. If SWU supply is physically limited, and uranium supply is limited to the WNA Reference case, or lower, prices for SWU could be even higher.

It is more likely that uranium supply (including secondary supply) will not reach the WNA Reference level and that tails assays will ultimately be lower than 0.27%. This will increase demand for enrichment services.

Recently, some enrichment suppliers have indicated that they will not write new contracts below 0.30% tails assay. Enrichers have experienced problems as customers have nominated low tails assays, requiring enrichment plants to operate at higher than utility-nominated tails assay, just to meet customer requirements for EUP. Temporary stopgaps include purchasing uranium to overfeed, or sending tails to Russia, with both uranium and SWU being returned to the west to meet contractual requirements.

A minimum limit on enrichment tails assay, in effect, limits the ability of utilities to substitute SWU for uranium, ensuring higher uranium demand. If this restriction were universally applied, *Figure 2* indicates that enrichers could increase SWU prices even more, to about US$270/SWU, assuming the uranium price remains at US$140/kgU. But uranium price would then likely increase more to compensate. Such a higher limit on tails assay may also arise simply through the need to ration scarce SWU supplies.

We should note that because there is likely not enough SWU to operate at a low Western average tails assay, uranium prices may continue to rise over the decade. If they do, enrichers may compete to capture part of this increase in price by offering *incremental* SWU at higher prices to substitute for uranium, and uranium suppliers *incremental* uranium to substitute for enrichment. This also seems likely to keep spot prices on upward trajectories for both.

The dual scarcity of uranium and enrichment might be solved through additional supplies of uranium or enrichment. For enrichment, additional supply might come from continuing operation of remaining gaseous diffusion plants, if that is possible, or through substantial imports of SWU from Russia. In the WNA Reference Case, continued operation of Paducah and GBI in France would come close to solving the problem, albeit at the high prices discussed above. The addition of significant Russian supply could then allow utilities to go to lower tails assays, reducing uranium demand and prices.

While Russia has long been seen as a source of low-cost SWU, a newly commercially astute Russia seems likely to charge higher prices for solving the Western supply problem. Given growing Russian internal and export requirements and lack of uranium, it is not obvious that it can do so in any case. Russia is only slowly adding SWU capacity (largely by replacing old centrifuges with new ones at marginally higher capacities) and will have to use it to extract maximum fuel from limited uranium supply for a growing fleet of domestic and export reactors if its current plans succeed.

For uranium, there is little alternative other than additional supply from government inventories. Unfortunately, history has shown that government sales tend to limit investment and production by commercial uranium companies, so the supply is probably not directly additive. Moreover, these inventories are quite limited relative to the scope of the problem.

An Unpleasant Complication

In the analysis so far, we have assumed that all market players see the same market signals in the long-term and make adjustments accordingly. However, those utilities with long-term contracts for uranium or SWU, or both, at low prices and with high flexibilities, can dramatically alter market conditions for those utilities without such contracts.

Much of Western centrifuge capacity was built on the basis of long-term contracts at attractive SWU prices and considerable tails flexibility. Utilities with such contracts, and faced with high uranium prices, are likely to nominate quite low tails assays-about 0.20%. This group of utilities will thus absorb much more than its fractional share of western SWU capacity, leaving less for others.

For example, suppose half of western utilities have such legacy contracts and exercise the right to enrich at 0.20% tails. Total Western reactor requirements in the WNA Reference Case are about 42.5 million SWU at 0.27% tails assay (about 6,740tEUP). Let us further assume that total supply is about 42.5 million SWU. But if the lucky utilities with low-cost SWU contracts operate at 0.20% tails assay, this absorbs not 21.2 million SWU of capacity but rather 24.8 million SWU. This leaves only 17.7 million SWU for those without such good contracts. The latter would have to enrich at 0.37% tails assay to produce the needed EUP.

Of course, the first group would deliver less uranium, about 3,800tU less than at 0.27% tails. Enrichers might buy this uranium to overfeed, or utilities without good enrichment contracts might buy it to produce EUP at the higher 0.37% tails assay. However, the problem is that producing half of total EUP at the higher assay requires not 3,800tU more but 8,100tU more than would be needed at 0.27%. The net result is a need for 4,300t more uranium overall. That is, SWU and uranium are so inefficiently allocated that it alters the supply/demand balance for uranium and enrichment. This is because going to lower tails assay for half of the EUP is a non-linear process-SWU are used inefficiently as tails assays decline and one must substitute a lot of uranium for SWU to make up the remainder.

Legacy contracts for enrichment thus prevent or delay longer-term market adjustment and introduce ultimately costly inefficiencies by isolating buyers from new market realities. The same is also true for uranium contracts. Low prices in legacy uranium contracts, particularly when combined with liberal upward flexibilities, encourage utilities faced with higher SWU prices to choose higher tails assays and thus “waste” uranium in the tails, reducing the amount available to other utilities. Both types of legacy contracts ultimately drive up prices for uranium and SWU.