

Enrichment's Critical Role in Nuclear Fuel Supplies

BY Y. LYDIA HSIEH AND JEFF COMBS

Most academic articles that deal with nuclear fuel focus on the uranium resource aspect of the fuel.¹ This is especially the case when examining the long-term prospects for the fuel, as the adequacy and price of the fuel becomes more of an issue.² However, the enrichment technology dimension of nuclear fuel is critically important since most reactors are of the light water variety and require enriched uranium to operate. Importantly, uranium and enrichment are substitutes, and this degree of substitutability only increases with advances in enrichment technology, as history has demonstrated.

Enrichment Technology: Impact on the Need for Uranium

The impact of enrichment technology on nuclear fuel has not been completely ignored. In 1989, Combs noted the potential for technology to substitute for uranium resources in the making of nuclear fuel, an observation made when examining the potential for investing in advanced enrichment technology.³ Combs pointed out that enrichers could not only expand their share of the enrichment market by investing in advanced technology and achieving cost advantages, but they could also gain business at the expense of the uranium market as well, as newer technology could displace the need for uranium to a greater degree.

With a more advanced technology, the enrichment process can be more efficient and recover more of the fissile content of the uranium, the isotope that sustains a nuclear reaction. In this way, it is like the fracking development in recovering oil and natural gas. This efficiency or effectiveness of enrichment is denoted by the tails assay, the fissile contained in the waste stream. In nature, the portion of U-235 contained in uranium is 0.711%. Uranium is typically enriched to 4-5% for light water reactors. As the tails assay drops, relatively more enrichment is used compared with uranium in the make-up of the fuel. When the operating tails assay (the assay at which enrichment occurs) is less than the transaction tails assay (the assay on which the quantity of uranium delivered to the enricher is based), it creates a situation known as underfeeding, where the enricher keeps the additional uranium that is not used in the enrichment process. The net effect of this greater use of enrichment is that less uranium needs to be produced to make an equivalent amount of enriched product.

Figure 1 presents the isoquant curve of EUP production using uranium (or feed) and enrichment (measured as separative work unites or SWU) as two inputs. In this example, we assume the feed is enriched to 4.50% of 1 kgU EUP at a tails assay ranging from 0.10% to 0.30%. The isoquant curve provides an illustration of using the substitutability of uranium (or feed) and enrichment to produce a fixed amount

of EUP. At each level of tails assay, the amount of uranium and SWU required to produce EUP are derived from mass and energy conservation equations based on feed-to-product ratio (F/P) and SWU-to-product ratio (S/P), respectively. For example, at a tails assay of 0.25%, the combination of 9.219 kgU of feed and 6.871 kg SWU is required to produce 1 kgU of EUP with a content of 4.5% U-235. If the tails assay is lowered to 0.20%, we could produce 1 kgU of EUP using less feed of 8.415 kgU and more enrichment of 7.691 kg SWU. At lower tails assays, even less uranium would be required.

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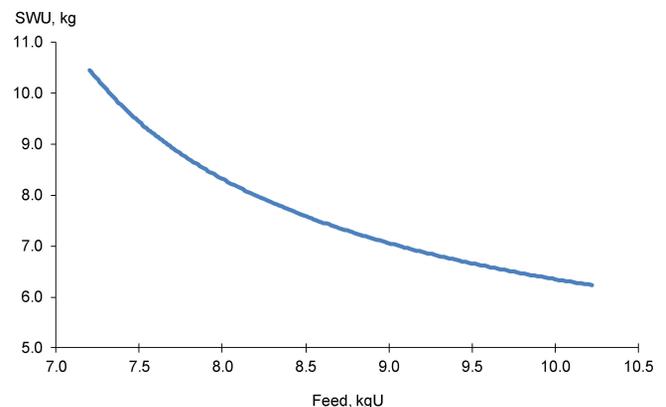


Figure 1. EUP Isoquant: Uranium and SWU Substitution

Tails Re-enrichment: Second-Order Effect of Enrichment for Uranium Substitution

Tails material – the waste product of the enrichment process – can be enriched to the level of natural uranium to further reduce the need for newly produced uranium, as long as the enrichment occurs at a lower tails assay than the assay of the material being enriched. For example, tails with a content of 0.25% U-235 can be enriched to 0.711% (the equivalent of natural uranium). If the operating tails assay is 0.10%, a 1 million SWU enrichment plant can produce 1.5 million pounds U_3O_8 equivalent. This re-enrichment of the waste stream has the impact of reducing the demand for newly produced uranium (i.e., the demand on uranium resources) by augmenting the supply of uranium. Thus, enrichment technology not only can economize on the need for uranium resources in the first instance by reducing demand but can more completely process tails material to augment uranium supply, further reducing the need for uranium resources.

Recent Developments

Now that three decades have passed from the Combs' paper, it is instructive to examine the extent to

which this substitution has taken place. Over this time, advances have been made in centrifuge technology that have lowered costs and allowed enrichment to take place at lower tails assays. As a result of this and greater competition, higher-cost gaseous diffusion enrichment technology has been phased out. Also, a new laser enrichment technology has been developed that promises even lower costs and a greater ability to physically substitute enrichment for uranium. In addition, during this time the Fukushima reactor accident occurred, resulting in the shutdown of a number of reactors and slower nuclear power growth, creating an environment for an even greater substitution of enrichment and uranium due to the relative economics of each and an abundance of excess enrichment capacity.

One of the results of this technology change has been enrichers operating their enrichment plants at very low tails assays both because it is more economical to do so and to utilize their excess capacity.⁴ The net effect of this greater use of enrichment is that less uranium needs to be produced. As discussed, the substitution of enrichment for uranium has not just been limited to underfeeding, tails re-enrichment has also played an important role in recent years. In this regard, Russia converted its Angarsk enrichment plant with a 3 million SWU capacity to the enrichment of tails material, producing an equivalent of 4.5 million pounds of U_3O_8 equivalent per year.⁵ URENCO, a major multinational enrichment corporation, also increased its ability to enrich tails material, while also engaging in considerable underfeeding. In June of 2013, it announced its “SWU for U” program where excess capacity is used to supplant or create uranium.

Figure 2 below shows the growth of enrichment demand or usage relative to that of uranium over the 1990 to 2017 period. Enrichment usage includes both enrichment of natural uranium and enrichment of tails material to the level of natural uranium.

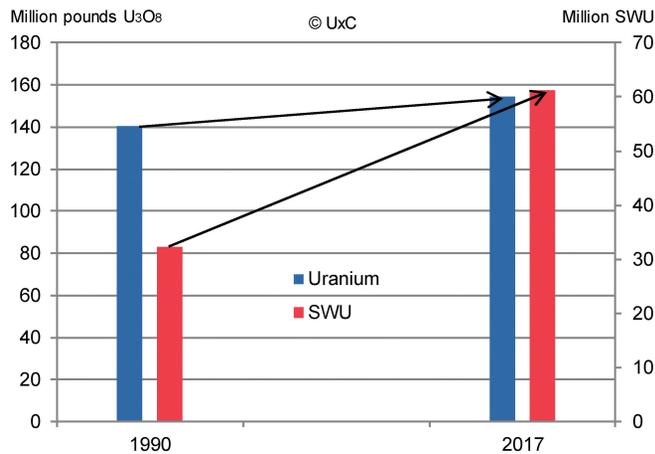


Figure 2. Relative Growth in Uranium vs. Enrichment Demand

Because of the increasing role that enrichment has played, it is estimated that only slightly more uranium production is needed today than was the case thirty years ago, even though installed nuclear capacity

has grown 20% over this period. This explains why uranium prices, until recently, have been lower in real terms than they were in 1990, after suffering a price spike associated with the entry of China into the market to fuel its ambitious nuclear power expansion plans and related hedge fund speculation, disruption of mine production, and the existence of trade restrictions that have since been relaxed.

The substitution of enrichment for uranium was accelerated by the reaction to the Fukushima reactor accident in 2011 and the subsequent drop in nuclear fuel demand that resulted in considerable excess enrichment capacity that has been used to create uranium and supplant its use. This substitution also explains why uranium inventories have grown so much. Current uranium inventories are estimated at 1.7 billion pounds, up considerably over the past decade. Not nearly as much uranium needed to be produced to meet reactor requirements, and it is likely that uranium producers did not fully understand the impact of this development, resulting in considerable overproduction. The massive inventory level coupled with the decline in forecasted demand is the reason that uranium prices have fallen. Uranium prices now reside below \$30, down from above \$70 before the Fukushima accident due to the reduced demand for uranium and the large inventory overhang. Enrichment prices have similarly suffered a large drop.

It is important to note that commercial laser enrichment technology, the advanced technology being discussed thirty years ago, still has not been introduced. Laser enrichment has even greater efficiency than centrifuge, able to operate at lower tails assays and thus requiring even less uranium to make a given quantity of enriched uranium.⁶ Because of its enhanced abilities, laser enrichment can more efficiently process tails material as well. In this regard, in 2013 the U.S. Department of Energy (DOE) selected a non-binding proposal by Global Laser Enrichment (GLE) to construct a tails enrichment facility using the SILEX technology at the DOE site in Paducah, Kentucky. DOE currently has about 114,000 MTU of high-assay tails material. Processing these at the proposed tails enrichment plant would result in another 5 million pounds U_3O_8 of natural uranium equivalent being produced on an annual basis, similar to the output of the Angarsk plant. However, due to poor economics related to depressed uranium prices, which ironically was in large measure due to enrichment supplanting the need for uranium, the GLE venture is not proceeding at this point.

It is noteworthy that a SILEX laser enrichment can also be used to perform normal toll enrichment in addition to enriching tails material. It thus can further economize on uranium usage while creating equivalent natural uranium by processing tails, thus both reducing uranium demand and augmenting uranium supply. In this respect the Silex technology would result in even further substitution of enrichment for uranium in the future when it is deployed.

Implications for Modeling

The ability to substitute enrichment and uranium has important implications for modeling and forecasting uranium and enrichment demand and prices. UxC has applied this concept to develop its two proprietary price forecasting models, U-PRICE® and SWU-PRICE® models.

Both U-PRICE and SWU-PRICE models are recursive econometric simulation models that consider the inter-relationships among key factors influencing the uranium and enrichment markets, respectively. This type of modeling allows us to incorporate related market and economic variables as an integral part to forecast uranium and SWU prices. Specifically, our models measure how changes in various market variables (which could also affect other variables included in the model) will impact future prices of uranium and SWU. Because of the recursive nature, when these models are simulated as a complete system, the value of each endogenous variable is determined sequentially. In addition, most exogenous variables in these models represent data of qualitative nature. These variables help measure the impacts of market uncertainties on both uranium and SWU prices.

Figure 3 presents the basic structure of the U-PRICE Model.

As illustrated in the above diagram, while the outlook of the nuclear industry is the key factor affecting both uranium demand and supply, economic and political factors external to the uranium market will also impact its price. For example, on the supply side, exchange rates between the U.S. dollar and home currencies of enrichers could affect enrichers' production cost and thus their cost competitiveness. On the demand side, changes in utility's fuel procurement and inventory strategies could have a significant impact on the timing and volume of uranium demand.

One factor that could affect both uranium demand and supply at the same time is the SWU price and SWU production capacity. This is because the substitutability between uranium and enrichment allows the consumers (i.e., utilities) and the suppliers

(i.e., enrichers) to vary tails assays to achieve intended operating goals. For utilities, when uranium becomes relatively more expensive than enrichment, shifting to lower transaction tails as allowed in an enrichment contract will help save fuel cost. For enrichers, using lower operating tails assay will help reduce excess production capacity. However, it should be emphasized that the key driver of these business practices is the relative price of uranium (or feed) to SWU, and not just the level of the uranium or SWU price. Figure 4 provides a more detailed look at how the model handles the uranium/enrichment interaction.

This brings up an important aspect in modeling the uranium and enrichment markets. Due to persistent oversupply in the uranium market and excess capacity in enrichment production, competition between uranium and enrichment has intensified in recent years. Accordingly, uranium and SWU prices are not truly independent of each other but depend on what the other market does. In both U-PRICE and SWU-PRICE models, the price ratio of uranium to SWU is used as one of the input variables that links the interactions of the two markets. Early work has shown when the term price of SWU is used as an independent variable in modeling uranium prices, the resulting uranium price forecast is notably lower than when this variable is not taken into consideration. The same is true when the spot price of uranium is used as an independent variable when modeling enrichment prices. Therefore, linking the U-PRICE model to the SWU-PRICE model will form an integrated framework that explicitly models the impact of the substitutability, and more importantly, the price interdependency between uranium and SWU. With a fully integrated model of the front-end market, the prices of uranium and SWU will be solved and forecasted simultaneously.

Policy Implications

Understanding the relationship between enrichment and uranium continues to be important for

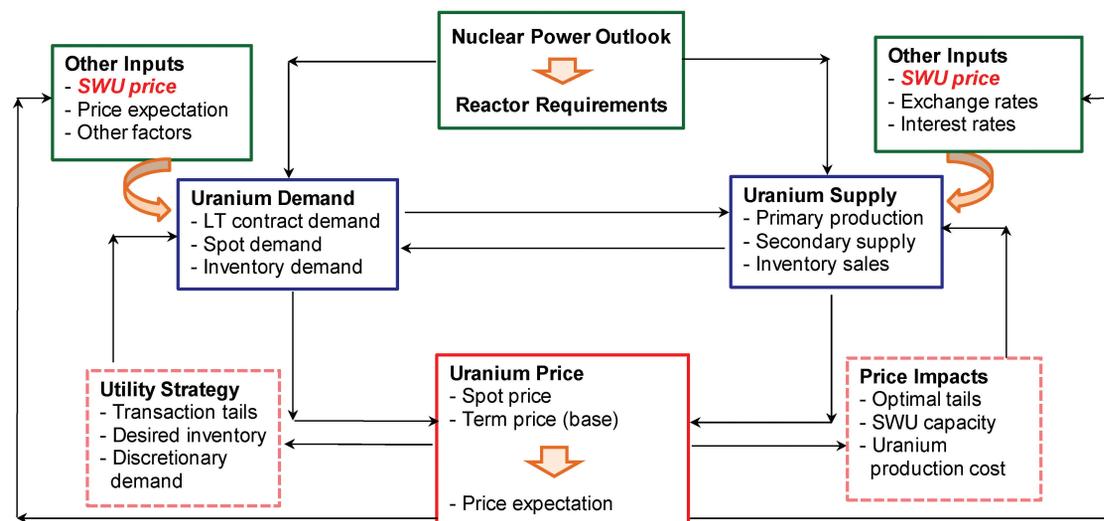


Figure 3. Basic Structure: U-PRICE Model

policymakers as well as nuclear fuel suppliers and consumers. In the past, fears have been expressed that the world is running out of uranium or that uranium prices will be pushed to extremely high levels as demand for nuclear energy rises.⁷ This concern may be voiced again if nuclear energy

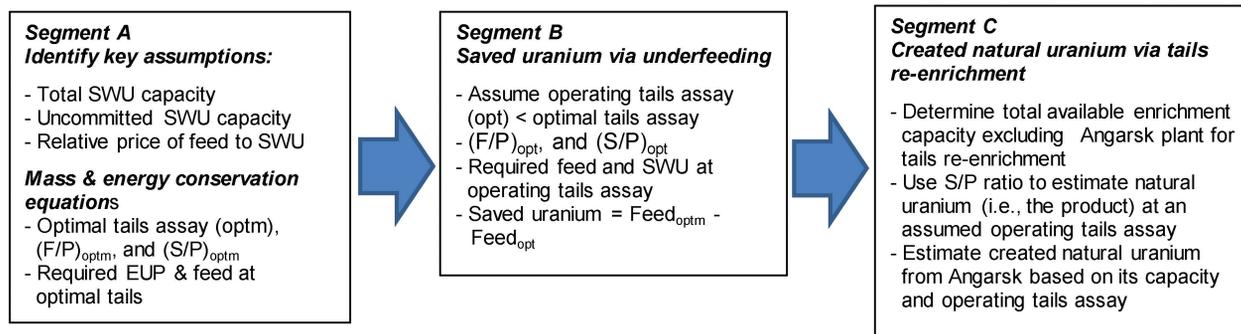


Figure 4. Model Structure: Quantifying Uranium & SWU Substitution

is expected to play an important role in combatting climate change.⁸

Concerns about the future availability of uranium have spurred efforts to develop breeder reactors which create their own fuel, plutonium, raising nonproliferation concerns.⁹ Other efforts include reprocessing spent fuel and recycling the recovered uranium and plutonium in reactors. These have been quite expensive and have also raised proliferation concerns.

Incorporating the substitution of enrichment for uranium into the analysis suggests that the need to invest in new reactor technologies for fuel efficiency reasons is less pressing although investments for increased reactor safety continue to be important. This is especially true if nuclear power is not growing to any great degree, which is currently the case. Of course, a key question is the degree to which nuclear power grows in the future. Here, climate considerations and other factors play a key role. If nuclear power is to continue to have prominent role in energy and environmental security, enrichment will need to play a key role in fuel availability and security.

Related to the outlook for nuclear energy, there is a danger in shuttering enrichment capacity prematurely, as it represents a resource hedge and to some degree a nonproliferation hedge. There exists considerable potential for enrichment to substitute for uranium, and this potential only will increase with advances in enrichment technology. The question is how the market and governments value these hedges. The United States has its “gold standard” when it comes to signing nuclear cooperation agreements (so-called 123 agreements) with other countries. This standard involves countries forswearing the development of uranium enrichment capabilities in exchange for access to U.S. reactor technology. There are also several fuel banks of enriched uranium around the world.¹⁰ Of note, the International Atomic Energy Agency has instituted such a fuel bank in Kazakhstan, as a way of helping to assure countries of future enriched supplies. However, these approaches depend on having an adequate base-line supply of enrichment capacity. If there is a reduction in this enrichment capacity, countries may be compelled to build their own enrichment plants, as a fuel bank does not represent

a long-term source of enrichment supply but is only a stopgap measure.

Enrichment may have an even more important role to play when it comes to advanced reactors, which can make use of high assay, low-enriched uranium (HALEU) where uranium is enriched above the 4-5% currently used in light-water reactors, potentially up to 20%. Smaller advanced reactors may be more amenable to countries just entering the nuclear power space, like those in Africa that are considering nuclear energy. What is interesting is that reactors loaded with HALEU can operate for many years, making fuel supply assurance less of an issue and, in essence, becoming mini fuel banks themselves. Thus, enrichment technology may become even more important in the future, not just because of its ability to extend uranium resources, but because of how reactor technology and related fuel needs are likely to change over time.

Footnotes

¹ One of the earliest papers was by Owens, A.D. (1985), “Short-Term Price Formation in the U.S. Uranium Market,” *The Energy Journal*, July 1985.

² See, for example, Gabriel, Sophie, Monnet, Antoine, and Percebois, Jaques (2017), “Uranium Resources and Security of Supply,” *IAEE Energy Forum*, Fourth Quarter 2017.

³ Combs (1989), “The Economics of Strategic Choice: U.S. Enrichment in the World Market: A Comment,” *The Energy Journal*, January 1989.

⁴ There are operational issues associated with shutting down and restarting centrifuges as they are designed to keep spinning.

⁵ This is based on a tails with an assay of 0.25% being enriched at a tails assay of 0.10%. It should be noted that Russia, which has relatively poor uranium resources but huge enrichment capacity from its military program, has engaged in tails enrichment for some time. See Bukharin, O. (1996), “Analysis of the Size and Quantity of Uranium Inventories in Russia,” *Science & Global Security*, Volume 6, no. 1 (1996)

⁶ Reportedly, laser enrichment can operate at well below a 0.10w/o tails assay.

⁷ Sharply rising uranium prices was a conclusion of the analysis appearing in “Uranium and Security of Supply,” which did not factor in the impact of enrichment on uranium supplies.

⁸ A number of studies have concluded that carbon abatement targets cannot be attained without nuclear energy. For example, see “The Future of Nuclear Energy in a Carbon-Constrained World,” by the MIT Energy Initiative.

⁹ Recently, China has started a fast-breeder reactor.

¹⁰ There are fuel banks in Russia, the United States, and Kazakhstan.