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Enriched-Uranium Feed Costs for the High-Temperature Gas-Cooled Reactor: Trends and Comparison with Other Reactor Concepts

MASTER

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ENRICHED-URANIUM FEED COSTS FOR THE HIGH-TEMPERATURE
GAS-COOLED REACTOR: TRENDS AND COMPARISON
WITH OTHER REACTOR CONCEPTS

W. E. Thomas

APRIL 1976

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GAS-COOLED REACTOR: TRENDS AND COMPARISON
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ABSTRACT

This report discusses each of the components that affect the unit cost for enriched uranium; that is, ore costs, U_3O_8 to UF_6 conversion cost, costs for enriching services, and changes in transaction tails assay. Historical trends and announced changes are included. Unit costs for highly enriched uranium (93.15% ^{235}U) and for low-enrichment uranium (3.0, 3.2, and 3.5% ^{235}U) are displayed as a function of changes in the above components and compared. It is demonstrated that the trends in these cost components will probably result in significantly less cost increase for highly enriched uranium than for low-enrichment uranium — hence favoring the High-Temperature Gas-Cooled Reactor.

Key words: HTGR, uranium, enriched materials, costs.

INTRODUCTION

The price that a utility, operating a High-Temperature Gas-Cooled Reactor (HTGR), must pay per kilogram of enriched uranium (93.15% ^{235}U) received from a gaseous diffusion cascade is a function of the following:

1. transaction tails assay,
2. cost for a unit of separative work (SWU),
3. unit cost paid for ore concentrates (U_3O_8) and associated cost for converting U_3O_8 to UF_6 .

Each of the above items is expected to change with time. This report examines the impact these changes may have on future costs for HTGR fresh feed and compares HTGR feed costs using highly enriched uranium with feed costs for other reactor types fueled with low-enrichment uranium.

The following section describes the method used to compute and compare feed costs, and subsequent sections discuss the announced changes in

transaction tails assay, and historical costs for SWU, ore concentrates, and conversion costs. The final sections are confined to the discussion of feed costs and cost comparisons.

CALCULATIONAL PROCEDURE

Reactor feed cost C , in dollars paid for fresh uranium enriched in ^{235}U content to some enrichment e , can be calculated from the following expression:

$$C = WC_e = W (C_f X_f + C_s X_s) , \quad (1)$$

where W is the amount of enriched uranium required per loading (kg) and C_e is a unit cost (\$/kg) for enriched uranium. The loading W is fixed by reactor design; C_e is a function of the unit cost for natural uranium C_f , the feed component X_f , the unit cost for enriching services C_s , and the separative work component X_s . Feed and separative work components depend entirely on the ^{235}U content in product, normal feed, and tails at the gaseous diffusion plant [see Eqs. (A2) and (A3) in Appendix A]. The unit cost for natural uranium is the sum of the unit cost for ore concentrates (U_3O_8) and the unit cost for conversion to UF_6 . As used in Eq. (1), C_f represents a cost delivered to the cascade feed station, including sampling and transportation charges and accounting for processing losses.

Consider two different reactors producing the same thermal power. One reactor requires a loading of W kilograms of enriched uranium per year at enrichment e_1 , costing C dollars per loading. The other reactor is fueled with enriched uranium at enrichment e_2 and requires a loading of W' kilograms per year, costing C' dollars per loading. The ratio of cost per loading is

$$\frac{C}{C'} = \frac{C_{e1} W}{C_{e2} W'} \propto \frac{C_{e1}}{C_{e2}} = \frac{X_f}{X'_f} \left[\frac{(C_f/C_s) + (X_s/X_f)}{(C_f/C_s) + (X'_s/X'_f)} \right] . \quad (2)$$

Since the quantities W and W' are the amounts of enriched uranium charged to maintain criticality during reactor operation and are fixed by reactor design, the ratio of loading costs becomes proportional to the

ratio of unit costs paid for enriched uranium at each enrichment e_1 and e_2 being investigated. The ratio of loading costs depends on the ratio of unit price paid for natural uranium feed C_f to unit charge for enrichment services C_s (hereafter referred to as the feed/SWU cost ratio). In Eq. (2), feed components and separative work components shown with primes refer to enrichment e_2 , and unprimed quantities refer to enrichment e_1 .

Equation (2) provides a convenient means for comparing costs for purchasing highly enriched uranium to fuel an HTGR with those of low-enrichment uranium for other reactor types (e.g., PWRs), considering changes in transactions tails assay and changes in unit costs for ore, conversion, and enriching services.

TRANSACTION TAILS ASSAY

In a gaseous diffusion plant the term operating tails x_w denotes the weight fraction of ^{235}U contained in "depleted" uranium (weight fraction somewhat less than natural uranium). The transaction tails assay lists values for x_w specified by the U.S. Energy Research and Development Administration (ERDA) (formerly AEC) in documents such as the *Federal Register* for use in computing feed requirements and separative work units. In the event that the transaction tails assay is specified somewhat lower than that of the operating tails, the government makes up the difference in feed requirements from reserves.

The transaction tails assay influences the values for X in Eqs. (1) and (2). An increase in the transaction tails assay increases the feed component (i.e., X_f and X'_f) but decreases the separative work component (i.e., X_s and X'_s) [see Eqs. (A2) and (A3) and Table A1 of Appendix A].

In June 1975, ERDA announced the following schedule of values for the transaction tails assay:¹

x_w	Effective date
0.002	Through 9-30-77
0.0025	10-1-77
0.00275	7-1-79
0.003	10-1-81

CHARGES FOR SEPARATIVE WORK

Events² leading to ownership by private industry of special nuclear materials and toll enrichment are summarized here. The Atomic Energy Act of 1954 permitted private industry to own all components of a nuclear power plant except the enriched-uranium fuel and the plutonium produced in the reactor. Possession and use of special nuclear materials by private industry was under license from the USAEC. Fuel costs were paid in the form of a use charge. The Private Ownership of Special Nuclear Materials Act, approved Aug. 26, 1964, eliminated this exclusion and permitted private industry to own the enriched uranium and plutonium. In 1966, the USAEC published the criteria under which it would perform toll enrichment of privately owned uranium and in 1967 published the first schedule of charges for this service. Toll enrichment of privately owned uranium began Jan. 1, 1969.

Under this concept, the USAEC received privately owned uranium and performed ^{235}U enrichment services for which the customer paid a "toll" charge. The charges per SWU that appeared in the various issues of the *Federal Register* are given in Table 1. Separate charges according to contract type first appeared in the *Federal Register* Aug. 9, 1973. In the *Federal Register*, the two contract types are referred to as "requirements type" and "other than requirements type." The term "fixed-commitment contract" has sometimes been used to mean "other than requirements-type contract." ERDA³ defined the contract types as follows: "Under a fixed-commitment contract, a customer specifies in advance the amount of enriching services he requires, thus obligating himself to a 'fixed' amount of these services. Under a requirements-type contract, ERDA is obligated, within limits, to provide a customer with the amount of enriching services he requires."

SWU costs from Table 1, together with the announced approximate increase³ (~\$76) for fixed-commitment contracts, are plotted in Fig. 1. The true costs beyond December 1975 will depend on action on the ERDA draft bill which was forwarded to Congress on June 24, 1975.

Fig. 1. Charge per separative work unit — current dollars. (See Ref. 3 and Table 1.)

Table 1. Costs for enrichment services -- historical data

Cost per SWU (current dollars)	Contract type ^a	Effective date	Source: <i>Federal Register</i> (volume, page, date)
26.0		Jan. 1, 1968	32FR16289; Nov. 29, 1967
28.70		Feb. 22, 1971	35FR13547; Aug. 25, 1970
32.00		Sept. 6, 1971	36FR4563; Mar. 9, 1971
38.50		Aug. 14, 1973	38FR4432; Feb. 14, 1973
38.50	R	Aug. 14, 1973	38FR21518; Aug. 9, 1973
36.00	F	Aug. 14, 1973	
38.90	R	Jan. 1, 1974	
36.40	F	Jan. 1, 1974	
39.30	R	July 1, 1974	
36.80	F	July 1, 1974	
47.80	R	Dec. 18, 1974	39FR22182; June 20, 1974
42.10	F	Dec. 18, 1974	
53.35	F	Aug. 20, 1975	40FR26060; June 20, 1975
60.95 ^b	R	Dec. 18, 1975	40FR26061; June 20, 1975

^aR = requirements type; F = fixed commitment.

^bOr ceiling charge, whichever is less.

UF₆ FEED COSTS

The unit cost for uranium contained in UF₆ feed to a gaseous diffusion plant is the sum of the unit cost for ore concentrates and the unit cost for converting U₃O₈ to UF₆. Costs for conversion and for ore concentrates are discussed separately below.

Conversion Costs

As of 1974, there were two commercial facilities in the U.S. capable of converting ore concentrates to UF₆. One is the Allied Chemical plant

at Metropolis, Ill. (capacity 14,000 tons/year), and the other is the Kerr-McGee Nuclear plant at Sequoyah, Okla. (5000 tons/year, with plans to increase future capacity to 10,000 tons/year).⁴ Allied's base charge, \$2.293 per kilogram of uranium, is referenced to year 1965; Kerr-McGee's base charge, \$2.49 per kilogram, has a base date of 1967.² Both rates are subject to escalation. It was estimated² as of Mar. 31, 1970, that the Kerr-McGee escalated rate, which includes sampling of ore concentrates and transportation of UF_6 to the gaseous diffusion plant, was \$2.74/kg; Allied's escalated rate, for conversion only, was ~\$2.64/kg. Lucius Pitkin, Inc., located adjacent to Allied's Metropolis plant, was sampling ore concentrates² (1970) for \$47.95 per gross ton or ~6.2¢/kg.

Conversion charges were reported⁴ to be running between \$3.00 and \$3.50 per kilogram in 1974, with future charges from new plants expected to be significantly higher because of increased construction costs and higher interest rates.

Conversion costs in late 1975 or early 1976 charged by Canada's Eldorado Nuclear⁵ were indicated to be about \$1.50 per pound of U_3O_8 (~\$3.90 per kilogram of uranium).

Ore (Yellowcake) Costs

The trends in unit costs for U_3O_8 concentrates are shown in Fig. 2. These data, in current dollars, were obtained from the literature.^{5-12,17-34} The detailed unit cost data appearing in the figure are discussed in Appendix B. An attempt was made to obtain at least one quotation of the price paid by the former USAEC during each year for the years 1959 through 1970 and to obtain as much unit cost data as practical to indicate the range of prices paid for yellowcake on the open, free, or commercial market.

The USAEC's uranium procurement program² extended over the 29-year period 1942 to 1970, inclusive. The average price paid by the government during that time was ~\$9/lb (\$19.85/kg) U_3O_8 , with ~54% of the total quantity, or ~176,000 tons (159.6×10^6 kg) of U_3O_8 , having been derived from domestic sources. The last foreign purchase commitment terminated in 1966, the year that also saw the first commercial sales of uranium concentrates.

Fig. 2. Yellowcake prices (historical).

UNIT COSTS AND COST COMPARISON

The scope of this analysis is limited to costs for fresh enriched uranium produced in a gaseous diffusion plant and to a fresh fuel purchase cost comparison between reactors using highly enriched uranium and reactors using low-enrichment uranium. As indicated by Eq. (2), the ratio of reactor loading costs paid for fresh fuel is proportional to the ratio of unit costs which must be paid for enriched uranium at each of the two fuel enrichments being investigated. Once the two fuel enrichments have been selected (e.g., 0.9315 and 0.032) and a transaction tails assay has been specified (e.g., 0.002, 0.0025, etc.), the ratio of unit costs for enriched uranium is entirely dependent on variations in the feed/SWU cost ratio, defined as dollars per kilogram of natural uranium feed divided by dollars per SWU enriching charge.

Historical Trends in Feed/SWU Cost Ratio

Figure 3 shows the variation in feed/SWU cost ratio during calendar years 1968 through the third quarter of 1975. Costs for enriching services (\$/SWU) are the same as those shown in Fig. 1, but only charges for fixed-commitment contracts are used in the latter years. Natural uranium feed costs at the cascade feed station were computed using annual commercial high and low unit costs for yellowcake (Fig. 2) and current conversion unit costs discussed in the previous section. Also shown in Fig. 3 are some feed/SWU cost ratios using specific unit costs for yellowcake. In 1968, the USAEC was paying \$8.00/lb U_3O_8 (\$17.64/kg), whereas prices paid on the early commercial market were somewhat less. The average price paid by USAEC⁶ for yellowcake during 1969 and 1970 was \$5.85/lb (\$12.90/kg), which was within the range of ore prices on the commercial market. The USAEC averages shown for years 1973 and 1974 are results from these surveys, which reflect average prices paid for yellowcake during those years and include contracts which had been written several years prior. The average yellowcake price⁷ for 1973 was \$7.10/lb U_3O_8 (\$15.66/kg), increasing⁸ to \$7.90/lb (\$17.42/kg) for 1974. Western Nuclear⁹ received a letter of intent for 1974 deliveries at \$9/lb (\$19.85/kg) and \$10/lb (\$22.05/kg)

Fig. 3. Ratio of UF_6 feed cost to cost per SWU.

for 1975 deliveries subject to escalation ($\sim$ \$11/lb or $\sim$ \$24.26/kg assuming 10% escalation rate). General Electric¹⁰ was offering small-scale producers slightly more than \$12/lb (\$26.46/kg) during the last half of 1975, whereas Washington Public Power Supply System¹¹ had awarded Canada's Rio Algom a contract for late 1975 and 1976 delivery at \$22/lb (\$48.51/kg).

It must be remembered that during the years from 1968 to 1975, enrichment costs increased from \$26/SWU in 1968 to \$53.35/SWU effective Aug. 20, 1975, for fixed-commitment contracts. Conversion costs also increased during the same period from $\sim$ \$2.50 to $\sim$ \$3.90/kg.

The average feed/SWU cost ratio (Fig. 3) during the years 1971 to 1974 was approximately 0.63. The years 1974 and 1975 show the range between high and low to be expanding, with low values reflecting cheap ore costs from long-standing contracts and high values generally reflecting the current yellowcake market. The present trend in feed/SWU cost ratio appears to be upward because ore costs are rising faster than enriching costs. The upward trend in ore costs from a depressed market can be appreciated by considering that the reported price¹² for concentrates during 1955 to 1958 was \$12.38/lb (\$27.30/kg), or approximately \$30/lb (\$66.15/kg) in equivalent 1975 dollars. Using the \$30/lb (\$66.15/kg) and \$53.35/SWU costs implies a feed/SWU cost ratio of $\sim$ 1.5, or $\sim$ 1.1 if the announced $\sim$ \$76/SWU enriching cost is used.¹

It is not the purpose of this report to forecast future costs for yellowcake, conversion, and enrichment service and hence trends in feed/SWU cost ratio; however, it is interesting to note that future prices for the above components from at least one such projection¹³ indicate that feed/SWU cost ratios will continue increasing for at least the next two decades. The results projected by Reichle¹³ for UF₆ cost (feed costs) and for enrichment services are reproduced below.

	1975	1980	1985	1990	1995
Feed cost, \$/kg U	69	96	135	189	265
Enrichment, \$/SWU	80	98	119	144	176
Feed/SWU cost ratio	0.86	0.98	1.13	1.31	1.51

Unit Costs for Enriched Uranium

Having discussed the parameter feed/SWU cost ratio, let us now consider the trends in unit costs for enriched uranium (\$/kg U) as a function of that parameter and also as a function of changes in transaction tails assay.

Figure 4 is a plot of unit costs for highly enriched uranium (93.15% ^{235}U) as a function of the feed/SWU cost ratio for two values for transaction tails assay (0.002 and 0.003) and for two costs for enrichment services (\$53.35 and \$100/SWU). For the 0.002 transaction tails assay, Fig. 4 indicates that late 1975 costs for highly enriched uranium might range from a low of ~\$16,000/kg U, provided yellowcake is available at ~\$5.50/lb U_3O_8 (\$12.13 \$/kg) to a high of ~\$25,000/kg U, assuming one paid ~\$24.50/lb U_3O_8 (\$54.02/kg) for ore concentrates.

Note also that the slopes of the lines in Fig. 4 increase with increasing values for transaction tails assay. If the transaction tails assay were changed from 0.002 to 0.003, the lines would intersect at a feed/SWU cost ratio of 0.8092 which is independent of enrichment; that is, if the product enrichment were 3% ^{235}U , or any other enrichment, the cost curves would still cross at the same feed/SWU cost ratio (see Appendix A for proof). Also as shown in Fig. 4, if the feed/SWU cost ratio is less than 0.8092, increasing the transactions tails assay from 0.002 to 0.003 results in lower unit costs for enriched uranium. The savings from lower enrichment cost (less SWUs required) outweigh cost increases from having to supply more natural uranium feed per kilogram of product. The reverse is true at the higher feed/SWU cost ratios.

The unit price for highly enriched uranium, which includes changes in transactions tails assay, unit enriching costs, ore cost, and conversion cost, may be obtained from Fig. 5. We illustrate the use of Fig. 5 by a numerical example. Suppose the unit cost for yellowcake is \$17.73/lb U_3O_8 (\$39.09/kg) and conversion costs, including sampling and transportation charges, are \$3.90/kg U. Excluding processing losses, feed cost is $(17.73 \times (2.6) + 3.90) \approx \$50.0/\text{kg}$ for natural uranium delivered to the cascade. Assume that the charges for enrichment services are \$100 per SWU with 0.002 specified for transaction tails assay. The feed/SWU cost ratio is $(\$50.0/\text{kg U}) \div (\$100/\text{SWU}) = 0.5$, and the ratio of enriched-uranium cost/SWU cost for

Fig. 4. Unit cost for enriched uranium (93.15% ^{235}U content).

Fig. 5. Costs for 93.15%-enriched uranium.

0.002 tails assay is 327. The price paid per kilogram of highly enriched uranium is $100 \times 327 \approx \$32,700/\text{kg}$. If the tails assay were 0.003 and all other parameters the same as above, the price would be $\approx \$31,300/\text{kg}$.

The unit price for low-enrichment (3.2% ^{235}U) is presented in Fig. 6.

If, for a specified transaction tails assay and various feed/SWU cost ratios, we divide the unit cost for highly enriched uranium by that for low-enrichment uranium, the results shown in Fig. 7 are obtained. These results, calculated using Eq. (2), indicate that as the feed/SWU cost ratio increases, the ratio of unit costs for enriched uranium (93.15% vs 3.2%)

Fig. 6. Costs for 3.2%-enriched uranium.

Fig. 7. Ratio of unit cost for 93.15%-enriched uranium to 3.2%-enriched uranium vs feed/SWU cost ratio.

decreases. Another way to state the results from Fig. 7 would be as follows: If future costs for ore concentrates plus conversion costs (i.e., feed costs) increase more rapidly than the costs for enriching services (condition of increasing feed/SWU cost ratio), the unit cost for highly enriched uranium will increase percentagewise less than that for low-enrichment uranium. As will be shown by the following numerical examples, cost trends that result in increased feed/SWU cost ratios yield cost advantages for the HTGR fueled with highly enriched uranium. Finally, it should be evident from Fig. 7 that changes in the ratio of unit costs for enriched uranium are least sensitive to changes in transaction tails assay. Only $x_w = 0.002$ and 0.003 are shown, whereas the first proposed change would be to 0.0025 , then to 0.00275 , and to 0.003 , each of which would produce results that generally would fall between the two curves shown in Fig. 7.

Loading Costs for HTGR vs PWR

To calculate the kilograms of natural and enriched uranium required for replacement loadings for an HTGR and a PWR (with plutonium recycle), we used the data from Table 12 of Ref. 14. For 0.2% tails assay and a 75% plant factor, the HTGR requires 0.085 short ton (77.1 kg) of U_3O_8 per megawatt of electricity [MW(e)] per year, and the PWR requires 0.129 ton (117.0 kg) which includes 0.0067 ton (6.08 kg) for natural uranium to be spiked with plutonium.¹⁴ The HTGR uses thorium as fertile material, reloading¹⁵ ~ 7.194 kg per megawatt [MW(e)] per year with an annual consumption of ~ 0.64 kg per megawatt [MW(e)]. These data formed the basis for the annual loadings shown in Table 2 for the 1000-MW(e) HTGR and the 1000-MW(e) PWR.

In the following cost analysis, we shall first ignore the PWR costs for natural uranium used as spiking material and the HTGR costs for thorium and concentrate on comparing the costs for enriched uranium. The unit costs for enriched uranium referred to in this analysis were obtained from Tables A2 and A4 of Appendix A assuming 0.2% tails assay.

As a base, or reference, case, we use 1975 costs for enriching services for fixed-commitment contracts (\$53.35/SWU) and 0.8 for a feed/SWU

Table 2. Uranium and thorium costs for a
1000-MW(e) HTGR and a 1000-MW(e) PWR

	PWR	HTGR
Enrichment, % ^{235}U	3.2	93.15
Enriched U loaded, kg/year	16,022	359.4
Natural U spiking, lb U_3O_8 /year	13,400	
Th load, none recycled, kg/year		7194
Th consumption, kg/year		~640
Reference case (\$53.35/SWU, feed/SWU cost = 0.8, \$14.91/lb U_3O_8) ^a		
Enriched U cost, \$/year	8,072,000	7,315,000
Natural U spiking, ^b \$/year	200,000	
Th cost, none recycled, \$/year		217,000 ^c
Th makeup, \$/year		19,300 ^c
Example 1 (\$53.35/SWU, feed/SWU cost = 1.4, \$27.22/lb U_3O_8) ^a		
Enriched U cost, \$/year	11,083,000	9,407,000
Cost increase above reference:		
Enriched U, \$/year	+3,011,000	+2,092,000
Enriched U, mills/kWhr(e)	0.458	0.318
Natural U spiking, ^b \$/year	+165,000	
Natural U spiking, mills/kWhr(e)	0.025	
Example 2 (\$100/SWU, feed/SWU cost = 1.4, \$52.34/lb U_3O_8) ^a		
Enriched U cost, \$/year	20,774,000	17,633,000
Cost increase above reference:		
Enriched U, \$/year	+12,702,000	+10,318,000
Enriched U, mills/kWhr(e)	1.932	1.569
Natural U spiking, ^b \$/year	+502,000	
Natural U spiking, mills/kWhr(e)	0.076	

^a Assuming conversion costs of ~\$3.90/kg.

^b As U_3O_8 , cost for subsequent conversion not included.

^c Based on \$12/lb ThO_2 .

cost ratio. The price for natural uranium (\$42.68/kg) could result from a conversion cost of \$3.90/kg quoted for late 1975 and \$14.91/lb U_3O_8 (\$32.88/kg) for ore concentrates [approximately arithmetic average between highest and lowest cost in mid-1975 (see Fig. 2)]. These costs would yield a unit cost for 93.15% enriched uranium of \$20,352.15/kg and would total approximately \$7.3 million for enriched uranium required to reload the HTGR; the unit cost for 3.2%-enriched uranium of \$503.79/kg, totaling approximately \$8 million for enriched uranium required for reloading the PWR (see Table 2).

We want to compare the increase in cost for purchasing enriched uranium to reload an HTGR with that for a PWR as costs for enriching services and/or costs for ore concentrates rise. As a first example, we allow the cost for enriching services to remain at \$53.35/SWU and arbitrarily increase the feed/SWU cost ratio to 1.4 from 0.8 specified for the reference case. This example would represent a sudden increase in price for ore concentrates from \$14.91/lb U_3O_8 (\$32.88/kg) to \$27.22/lb (\$60.02/kg) assuming conversion costs remained unchanged. Concentrate at \$27.22/lb U_3O_8 is not far above the highest cost shown in Fig. 2 for late 1975. This assumed increase in ore cost would place the unit cost for 93.15%-enriched uranium at \$26,174.70/kg and would result in approximately \$2 million increase in cost for enriched uranium for reloading the HTGR. As can be seen in Table 2, the increase in cost for enriched uranium would be even larger for the PWR. At the higher ore cost, the unit cost for 3.2%-enriched uranium would be \$691.71/kg, which would raise the cost for enriched uranium required to reload the PWR about \$3 million. Hence, the HTGR would be approximately \$1 million per year, or 0.14 mills/kWhr(e), less sensitive to this assumed sudden increase in price for ore concentrates than the PWR.

As conditions for the second example, we use the same feed/SWU cost ratio (1.4) as above but allow the cost for enrichment services to increase from \$53.35/SWU to an arbitrary choice of \$100/SWU. If conversion costs were assumed to remain at \$3.90/kg U, the unit cost for ore concentrates would be \$52.34/lb U_3O_8 (\$115.40/kg) to satisfy both the new costs for enriching services and the feed/SWU cost ratio. The unit costs for 93.15%- and 3.2%-enriched uranium would be \$49,062.23 and \$1,296.56/kg respectively.

Note that these unit costs are, respectively, ~ 2.4 and ~ 2.6 times the 1975 unit costs (reference case) for 93.15%- and 3.2%-enriched uranium. Ore costs, $\sim \$50/\text{lb } \text{U}_3\text{O}_8$ ($\$110.25/\text{kg}$), and charges for separation work, $\sim 100/\text{SWU}$, are in line with some predictions for these costs expected to occur within the next 5 to 10 years. As can be seen by the data in Table 2, relative to the reference case, the cost for enriched uranium to reload the HTGR has increased $\sim \$10.3$ million, and that for the PWR has increased $\sim \$12.7$ million. The difference in these increases [$\sim \$2.4$ million or $0.36 \text{ mill/kWhr(e)}$] shows that the HTGR is less sensitive than the PWR to the assumed increases in costs of ore and enrichment services. In the above example, we used 0.2% tails assay. If we had used 0.3% tails assay in computing unit costs for enriched uranium in example 2; the conclusions would have been essentially the same; that is, the HTGR would have been $\sim \$2.6$ million per year less sensitive to the rising costs than the PWR.

In the discussions above, we did not consider reactor reoptimization. The cost increase (above reference case) for enriched uranium required by the PWR could be somewhat less if the enrichment were reduced as the costs for both ore concentrates and separative work increase. However, a reduction in enrichment, assuming the amount of ^{235}U in the core is held constant, implies a larger PWR core and associated cost increase for components such as the pressure vessel. Since the objective of reoptimization would be to minimize the cost for electricity (which includes capital costs and costs for all components of the fuel cycle), it is not clear what effect, if any, attempts at reoptimizing a PWR might have on the above PWR-HTGR cost comparison.

Table 2 also shows the costs for natural uranium to be spiked with plutonium in a PWR and the cost for fresh thorium reloaded into an HTGR. The price^{1b} for nuclear grade, 99.9% ThO_2 , during 1974 was reported as $\$8$ to $\$12/\text{lb } \text{ThO}_2$ ($\$20.07$ to $\$30.11/\text{kg}$). The higher unit cost was used to calculate the thorium costs shown in Table 2. If spent thorium is not reclaimed and reused in the HTGR, the cost for fresh thorium will be approximately the same as the cost for natural uranium (as U_3O_8 excluding the cost for subsequent oxide conversion) required for mixing with plutonium in the PWR. If only the thorium consumed is to be replaced with fresh thorium,

the costs for this makeup will be quite small for an HTGR. The cost increase for natural uranium spiking material (PWR) is also shown in Table 2 for each of the two examples, that is, as yellowcake prices are assumed to increase from \$14.91/lb to \$27.22/lb or \$52.34/lb. As can be seen, the cost increase for this spiking material, relative to the cost increase for the 3.2%-enriched uranium, is quite small for the PWR.

CONCLUSIONS

If natural uranium feed costs (i.e., cost for ore concentrates plus U_3O_8 to UF_6 conversion costs) rise more rapidly in the future than costs for enrichment services, this trend toward increasing feed/SWU cost ratio will offer cost advantages for reactors such as the HTGR that use highly enriched uranium. The ratios of unit cost for highly enriched uranium to that for low-enrichment uranium decrease with increasing feed/SWU cost ratio (see Fig. 7). Under certain conditions, as illustrated by numerical examples, the cost increase for highly enriched uranium for loading HTGRs can be millions of dollars less than that for low-enrichment uranium required to load PWRs.

Over most of the range of feed/SWU cost ratios studied, an increase in transactions tails assay from 0.002 stepwise to 0.003 does not appear to offer any significant cost advantage or disadvantage for the HTGR relative to the PWR. The unit costs for highly enriched uranium and for low-enrichment uranium may each either increase or decrease as the transaction tails assay is increased. If the feed/SWU cost ratio is less than 1.0188, the first announced increase (from 0.002 to 0.0025) will result in a unit cost decrease for both highly enriched uranium and low-enrichment uranium; feed/SWU cost ratios greater than 1.0188 will cause the opposite effect (see Figs. 5 and 6).

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Appendix A

UNIT COSTS FOR ENRICHED URANIUM

The unit cost (\$/kg U) paid for enriched uranium C_e was expressed in Eq. (1) of the text as follows:

$$C_e = C_f X_f + C_s X_s, \quad (A1)$$

where C_f is the cost of natural uranium (\$/kg) at the cascade feed station and C_s is the cost for enriching services (\$/SWU).

The feed component, kilograms of natural uranium feed per kilogram of enriched uranium product, is

$$X_f = (x_p - x_w) / (x_f - x_w), \quad (A2)$$

where

x_p = product enrichment, wt % ^{235}U (e.g., 0.9315, 0.032 etc.),

x_w = tails enrichment, wt % ^{235}U (e.g., 0.002, 0.0025 etc.),

x_f = natural uranium feed enrichment, wt % ^{235}U (0.00711).

The separative work component, SWU/kg of enriched uranium product, is defined as

$$X_s = \phi_p + (W/P)\phi_w - X_f\phi_f, \quad (A3)$$

where

$$\phi_p = (2x_p - 1) \ln [x_p / (1 - x_p)],$$

$$\phi_w = (2x_w - 1) \ln [x_w / (1 - x_w)],$$

$$\phi_f = (2x_f - 1) \ln [x_f / (1 - x_f)],$$

$$W/P = (x_p - x_f) / (x_f - x_w).$$

The numerical values for feed component, separative work component, and other terms appearing in the cost equations are shown in Table A1. These values have been computed for highly enriched uranium (93.15% ^{235}U) and for low-enrichment uranium (3.0, 3.2, and 3.5% ^{235}U) and include anticipated transaction tails assays from 0.002 to 0.003. Tables A1 through A6 were prepared from machine listings. The terms appearing in each table

Table A1. Numerical values for terms in the unit cost equation

VALUES APPLICABLE TO HIGHLY ENRICHED URANIUM ($x_P=0.9315$)

PHI(P)=	2.25240			
	xw=0.00200	xw=0.00250	xw=0.00275	xw=0.00300
W/P	180.8982	200.5185	212.0161	224.9125
X(F)	181.8982	201.5185	213.0161	225.9125
X(S)	235.9651	215.9751	207.7253	200.3486

VALUES APPLICABLE TO LOW ENRICHMENT URANIUM ($x_P=0.0300$)

PHI(P)=	3.26753			
	xw=0.00200	xw=0.00250	xw=0.00275	xw=0.00300
W/P	4.4795	4.9653	5.2500	5.5693
X(F)	5.4795	5.9653	6.2500	6.5693
X(S)	4.3065	3.8115	3.6072	3.4245

VALUES APPLICABLE TO LOW ENRICHMENT URANIUM ($x_P=0.0320$)

PHI(P)=	3.19129			
	xw=0.00200	xw=0.00250	xw=0.00275	xw=0.00300
W/P	4.8708	5.3991	5.7087	6.0560
X(F)	5.8708	6.3991	6.7087	7.0560
X(S)	4.7464	4.2082	3.9860	3.7874

VALUES APPLICABLE TO LOW ENRICHMENT URANIUM ($x_P=0.0350$)

PHI(P)=	3.08461			
	xw=0.00200	xw=0.00250	xw=0.00275	xw=0.00300
W/P	5.4579	6.0499	6.3968	6.7859
X(F)	6.4579	7.0499	7.3968	7.7859
X(S)	5.4140	4.8109	4.5620	4.3394

VALUES COMMON TO ALL PRODUCT ENRICHMENT

PHI(F)=	4.86888	XF= 0.00711		
	xw=0.00200	xw=0.00250	xw=0.00275	xw=0.00300
PHI(W)	6.18776	5.95902	5.86099	5.77130

Table A2. Unit costs for highly enriched uranium (XP=0.9315)

\$/SWU= 53.35

XP= 0.9315 , XF= 0.00711

UNIT COST FOR ENRICHED URANIUM (\$/KG U AS UF ₆)				
(FEED/SWU)	XW=0.00200	XW=0.00250	XW=0.00275	XW=0.00300
0.200	14529.59	13672.46	13355.02	13099.08
0.400	16470.44	15822.66	15627.90	15509.57
0.600	18411.29	17972.86	17900.78	17920.05
0.800	20352.15	20123.07	20173.67	20350.54
1.000	22293.00	22273.27	22446.55	22741.02
1.200	24233.86	24423.47	24719.42	25151.51
1.400	26174.70	26573.67	26992.30	27561.99
1.600	28115.55	28723.88	29265.19	29972.47
1.800	30056.40	30874.07	31538.06	32382.96
2.000	31997.27	33024.28	33810.96	34793.45
2.200	33938.12	35174.48	36083.83	37203.93

\$/SWU= 100.00

XP= 0.9315 , XF= 0.00711

UNIT COST FOR ENRICHED URANIUM (\$/KG U AS UF ₆)				
(FEED/SWU)	XW=0.00200	XW=0.00250	XW=0.00275	XW=0.00300
0.200	27234.47	25627.86	25032.85	24553.11
0.400	30872.43	29658.23	29293.16	29071.36
0.600	34510.40	33688.60	33553.49	33589.60
0.800	38148.36	37718.97	37813.82	38107.86
1.000	41786.33	41749.34	42074.14	42626.10
1.200	45424.29	45779.71	46334.45	47144.36
1.400	49062.23	49810.08	50594.77	51662.60
1.600	52700.20	53840.45	54855.10	56180.83
1.800	56338.16	57870.80	59115.40	60699.09
2.000	59976.14	61901.20	63375.75	65217.36
2.200	63614.11	65931.56	67636.00	69735.56

Table A3. Unit costs for low-enrichment uranium (XP=0.0300)

\$/SWU= 53.35

XP= 0.0300 , XF= 0.00711

UNIT COST FOR ENRICHED URANIUM (\$/KG U AS UF₆)

(FEED/SWU)	XW=0.00200	XW=0.00250	XW=0.00275	XW=0.00300
0.200	288.22	266.99	259.13	252.79
0.400	346.68	330.64	325.82	322.89
0.600	405.15	394.29	392.51	392.98
0.800	463.61	457.94	459.19	463.08
1.000	522.08	521.59	525.88	533.17
1.200	580.54	585.24	592.57	603.27
1.400	639.01	648.89	659.26	673.36
1.600	697.48	712.54	725.94	743.46
1.800	755.94	776.19	792.63	813.55
2.000	814.41	839.84	859.32	883.65
2.200	872.87	903.49	926.01	953.74

\$/SWU= 100.00

XP= 0.0300 , XF= 0.00711

UNIT COST FOR ENRICHED URANIUM (\$/KG U AS UF₆)

(FEED/SWU)	XW=0.00200	XW=0.00250	XW=0.00275	XW=0.00300
0.200	540.24	500.45	485.72	473.84
0.400	649.83	619.76	610.72	605.23
0.600	759.41	739.07	735.72	736.61
0.800	869.00	858.37	860.72	868.00
1.000	978.59	977.68	985.72	999.39
1.200	1088.18	1096.98	1110.72	1130.77
1.400	1197.77	1216.29	1235.72	1262.16
1.600	1307.36	1335.59	1360.72	1393.55
1.800	1416.95	1454.90	1485.72	1524.93
2.000	1526.54	1574.21	1610.72	1656.32
2.200	1636.13	1693.51	1735.72	1787.71

Table A4. Unit costs for low-enrichment uranium (XP=0.0320)

\$/SWU= 53.35

XP= 0.0320 , XF= 0.00711

UNIT COST FOR ENRICHED URANIUM (\$/KG U AS UF ₆)				
(FEED/SWU)	XW=0.00200	XW=0.00250	XW=0.00275	XW=0.00300
0.200	315.86	292.78	284.24	277.35
0.400	378.51	361.06	355.82	352.63
0.600	441.15	429.34	427.40	427.92
0.800	503.79	497.62	498.98	503.21
1.000	566.43	565.90	570.56	578.49
1.200	629.07	634.18	642.15	653.78
1.400	691.71	702.46	713.73	729.07
1.600	754.36	770.74	785.31	804.36
1.800	817.00	839.01	856.89	879.64
2.000	879.64	907.29	928.48	954.93
2.200	942.28	975.57	1000.06	1030.22

\$/SWU= 100.00

XP= 0.0320 , XF= 0.00711

UNIT COST FOR ENRICHED URANIUM (\$/KG U AS UF ₆)				
(FEED/SWU)	XW=0.00200	XW=0.00250	XW=0.00275	XW=0.00300
0.200	592.06	548.80	532.78	519.86
0.400	709.43	676.78	666.95	660.98
0.600	826.39	804.77	801.13	802.10
0.800	944.31	932.75	935.30	943.22
1.000	1061.73	1060.73	1069.48	1084.34
1.200	1179.14	1188.71	1203.65	1225.46
1.400	1296.56	1316.70	1337.82	1366.58
1.600	1413.98	1444.68	1472.00	1507.70
1.800	1531.39	1572.66	1606.17	1648.81
2.000	1648.81	1700.64	1740.35	1789.93
2.200	1766.23	1828.63	1874.52	1931.05

Table A5. Unit costs for low-enrichment uranium (XP=0.0350)

\$/SWU= 53.35

XP= 0.0350 , XF= 0.00711

UNIT COST FOR ENRICHED URANIUM (\$/KG U AS UF ₆)				
(FEED/SWU)	XW=0.00200	XW=0.00250	XW=0.00275	XW=0.00300
0.200	357.74	331.88	322.31	314.58
0.400	426.65	407.11	401.23	397.66
0.600	495.56	482.33	480.15	480.73
0.800	564.46	557.55	559.08	563.81
1.000	633.37	632.77	638.00	646.89
1.200	702.27	708.00	716.92	729.96
1.400	771.18	783.22	795.85	813.04
1.600	840.09	858.44	874.77	896.11
1.800	908.99	933.66	953.70	979.19
2.000	977.90	1008.88	1032.62	1062.26
2.200	1046.80	1084.11	1111.54	1145.34

\$/SWU= 100.00

XP= 0.0350 , XF= 0.00711

UNIT COST FOR ENRICHED URANIUM (\$/KG U AS UF ₆)				
(FEED/SWU)	XW=0.00200	XW=0.00250	XW=0.00275	XW=0.00300
0.200	670.56	622.09	604.14	589.66
0.400	799.72	763.09	752.07	745.38
0.600	928.88	904.08	900.01	901.10
0.800	1058.04	1045.08	1047.94	1056.81
1.000	1187.19	1186.08	1195.88	1212.53
1.200	1316.35	1327.08	1343.81	1368.25
1.400	1445.51	1468.07	1491.75	1523.97
1.600	1574.67	1609.07	1639.69	1679.68
1.800	1703.83	1750.07	1787.62	1835.40
2.000	1832.99	1891.07	1935.56	1991.12
2.200	1962.14	2032.06	2083.49	2146.84

Table A6. Unit cost ratios for enriched uranium

(FEED/SWU)	93.15 PERCENT / 3.00 PERCENT			
	XW=0.00200	XW=0.00250	XW=0.00275	XW=0.00300
0.200	50.41	51.21	51.54	51.82
0.400	47.51	47.85	47.97	48.03
0.600	45.44	45.58	45.61	45.60
0.800	43.90	43.94	43.93	43.90
1.000	42.70	42.70	42.68	42.65
1.200	41.74	41.73	41.72	41.69
1.400	40.96	40.95	40.94	40.93
1.600	40.31	40.31	40.31	40.31
1.800	39.76	39.78	39.79	39.80
2.000	39.29	39.32	39.35	39.37
2.200	38.88	38.93	38.97	39.01

(FEED/SWU)	93.15 PERCENT / 3.20 PERCENT			
	XW=0.00200	XW=0.00250	XW=0.00275	XW=0.00300
0.200	46.00	46.70	46.99	47.23
0.400	43.51	43.82	43.92	43.98
0.600	41.74	41.86	41.88	41.88
0.800	40.40	40.44	40.43	40.40
1.000	39.36	39.36	39.34	39.31
1.200	38.52	38.51	38.49	38.47
1.400	37.84	37.83	37.82	37.80
1.600	37.27	37.27	37.27	37.26
1.800	36.79	36.80	36.81	36.81
2.000	36.38	36.40	36.42	36.44
2.200	36.02	36.06	36.08	36.11

(FEED/SWU)	93.15 PERCENT / 3.50 PERCENT			
	XW=0.00200	XW=0.00250	XW=0.00275	XW=0.00300
0.200	40.61	41.20	41.44	41.64
0.400	38.60	38.87	38.95	39.00
0.600	37.15	37.26	37.28	37.28
0.800	36.06	36.09	36.08	36.06
1.000	35.20	35.20	35.18	35.15
1.200	34.51	34.50	34.48	34.46
1.400	33.94	33.93	33.92	33.90
1.600	33.47	33.46	33.45	33.45
1.800	33.07	33.07	33.07	33.07
2.000	32.72	32.73	32.74	32.75
2.200	32.42	32.45	32.46	32.48

are as similar as possible, consistent with machine output, to the symbols appearing in Eqs. (A1) to (A3) and hopefully are recognizable (e.g., $X(F) = X_f$; $X(S) = X_s$; $XW = x_w$; $PHI(P) = \phi_p$, etc.).

Unit costs for highly enriched uranium (93.15% ^{235}U) as a function of transaction tails assay and feed/SWU cost ratio and for two costs for enrichment services (\$53.35/SWU and \$100/SWU) are shown in Table A2. Unit costs for low-enrichment uranium, 3.0% ^{235}U , 3.2% ^{235}U , and 3.5% ^{235}U , are shown in Tables A3, A4, and A5, respectively.

Table A6 displays the ratio of unit cost for highly enriched uranium to that for low-enrichment uranium. The results with 3.2% ^{235}U were incorporated into Fig. 7.

Indifference Feed/SWU Cost Ratio

As shown in Figs. 5 and 6, as the transactions tails assay values are changed (i.e., from 0.002 to 0.0025 to 0.00275 to 0.003), the linear functions relating the ratios (C_e/C_s) vs (C_f/C_s) will intersect at specific feed/SWU cost ratios, some unique value for the ratio C_f/C_s . At this "indifference" ratio, changing the transaction tails assay results in no change in the unit price paid for enriched uranium. If the price paid for ore concentrates, conversion, and enrichment services are such that the feed/SWU cost ratio (C_f/C_s) is greater than this "indifference" ratio, then increasing the transaction tails assay results in an increase in unit cost for enriched uranium and a reduction in unit cost for enriched uranium if the feed/SWU cost ratio is less than the "indifference" ratio. The "indifference" ratio is independent of ^{235}U enrichment x_p ; it is dependent only on x_f , the current transaction tails assay before change x_w , and the transaction tails assay after change x_w^* .

The independence of x_p can be proved as follows: Divide Eq. (A1) by C_s and require the ratio C_e/C_s to remain constant as x_w is changed to x_w^* ; then solve for the feed/SWU cost ratio C_f/C_s :

$$\frac{C_f}{C_s} = \frac{X_s^* - X_s}{X_f - X_f^*} = \phi_f + [(x_f - x_w) \phi_w^* - (x_f - x_w^*) \phi_w] / (x_w - x_w^*) .$$

The term ϕ_f is a function only of x_f ; ϕ_w is a function of transaction tails assay x_w before change; and ϕ_w^* is a function of transaction tails assay x_w^* after change.

The following table lists solutions to the above equation when considering several possible changes in the transaction tails assay.

<u>Change in transaction tails assay</u>	<u>Indifference feed/SWU cost ratio</u>
0.002 to 0.0025	1.01884
0.0025 to 0.00275	0.71754
0.00275 to 0.003	0.57201
0.002 to 0.003	0.80921

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Appendix B

HISTORICAL COSTS FOR ORE CONCENTRATES

This appendix acknowledges the sources of information appearing in Fig. 2. The presentation has been organized according to (1) prices paid by the former USAEC, (b) prices paid on the commercial market, and (3) projections. Where possible, unit prices paid each year starting with the earliest year is the intended format. Unit costs for ore concentrates (yellowcake) are usually reported in the literature in units of U.S. dollars per pound as U_3O_8 . These units have been preserved in this appendix. If the reader desires to convert to metric, multiply each unit cost by 2.205 for units of dollars per kilogram of U_3O_8 or by 2.60 for dollars per kilogram of uranium.

AEC Prices Paid for Ore Concentrates (U_3O_8)Before 1959

From 1955 to 1958, U_3O_8 prices¹² were \$12.38/lb (~\$30/lb in 1975 dollars). Canadian geologist Lattazi¹⁷ placed the 1952 to 1956 price in excess of \$11/lb and also stated that much of the uranium presently produced (1975) in the western world continues to come from long-standing facilities which were amortized at prices such as these.

1959

Franklin¹⁸ reported that the AEC paid \$9.40/lb for domestic concentrates, \$10.87/lb for Canadian, and \$11.84/lb for other foreign (presumably South African).

1960

According to Bernick,¹⁹ the AEC paid \$8.99/lb for domestic, \$11.04/lb for Canadian, and \$12.01/lb for "overseas" (presumably South African).

1961

Bernick²⁰ listed AEC prices at \$8.31/lb average for domestic and \$11.20/lb for South African concentrates.

1961-1963

Bernick²¹ reported average U_3O_8 prices paid in fiscal 62-63 as \$7.85/lb (domestic), \$9.77/lb (Canadian), and \$11.29/lb (South African).

1963-1964

Bracklin²² quoted AEC prices paid in fiscal 64 for average domestic as \$8.03/lb, Canadian as \$8.79/lb, and South African as \$11.32/lb.

1964-1965

Sherman²³ reported AEC prices paid for concentrates during fiscal 65 as \$8.03/lb for domestic, \$8.73 for Canadian, and \$11.08 for South African.

1966-1970

Hogerton's paper⁶ (May 1975) put a flat price of \$8/lb U_3O_8 for the years 1964 through 1968 and an average price of \$5.85/lb during the stretch-out phase (1969 to 1970).

Bernick²⁴ (Feb. 1963) quoted the "new" AEC prices would be \$8/lb from Mar. 31, 1962, through 1968 and then no more than \$6.70/lb in 1969 and 1970.

Commercial Prices Paid for Ore Concentrates (U_3O_8)

1966-1968

Sherman²⁵ reported early sales as ranging from \$4 to \$6/lb during 1966 and early 1967. Warren and Steyn²⁶ placed the worth of uranium concentrates in 1967 at \$6.00 to \$6.50/lb. Sherman²⁷ reported a 1967 average price for Canadian U_3O_8 of \$6.40/lb.

1968-1972

Sherman²⁷ listed some private sales for the near term as follows:

<u>Firm</u>	<u>Contract dates</u>	<u>Price (\$/lb U_3O_8)</u>
Kerr-McGee	1968-1970	5.85
	1970-1973	6.45
Utah Construction and Mining	1968-1971	5.39
	1972-1975	6.425
United Nuclear Corporation	1969-1977	6.14

1972-1974

Concentrates making the open market in 1972 and 1973 often sold for \$6.25/lb, frequently less than the cost of mining and milling it.¹² Gordon²⁸ reported spot prices at \$6.00 to \$6.50 per pound for 1972 and an average price⁷ of \$7.10 per pound for near-term deliveries in 1973.

1974, 1975

There was a considerable spread between the high and low costs for concentrates during the years 1974 and 1975. Contracts written in prior years for delivery during these years were at prices much lower than those specified in new contracts for immediate or near-term delivery.

The AEC survey²⁹ of contracts made from 1967 to mid-1974 places the average 1974 cost at \$7.65/lb. The ERDA survey,⁸ a year later, of contracts made from 1967 to mid-1975 increased the average 1974 cost to \$7.90/lb.

During 1974, Western Nuclear⁹ received a letter of intent for 1974 deliveries priced at \$9/lb and 1975 delivery at \$10/lb, subject to escalation. TVA³⁰ picked up its yellowcake option with United Nuclear, for delivery in the late seventies, at something over \$13/lb in 1975 dollars. General Electric¹⁰ was offering (mid-1975) slightly more than \$12/lb to small-scale producers in the Colorado Plateau area; Union Carbide was paying a little less than \$5/lb. Washington Public Power Supply System³¹ contracted with Canada's Rio Algom for late 1975 delivery at \$22/lb. Washington Public Power Supply System¹¹ also awarded a contract (June 1975) to Western Nuclear for 1979 to 1983 delivery at the current price of \$22/lb, subject to escalation.

In May 1974, Nuclear Exchange Corporation³² forecast \$11.25/lb for 1975 delivery. A year later Nuclear Exchange Corporation³³ placed the immediate delivery cost in May 1975 at \$20/lb, and it jumped³⁴ to \$24.70/lb in early August 1975.

Surveys and Projections

The former AEC and ERDA have each conducted surveys and reported weighted average uranium prices. The AEC results,²⁹ reported Oct. 22, 1974, reflect contracts with domestic producers made from 1967 through

mid-1974; ERDA⁸ results, reported Sept. 9, 1975, reflect contracts with domestic producers made from 1967 through mid-1975. The averages reported were not claimed to represent prices at which uranium may be purchased "now or in the future." The average prices per pound (estimated in current dollars) as they appeared in each reference are reproduced below:

<u>Calendar year</u>	<u>Average cost (\$/lb U₃O₈)</u>	
	<u>Ref. 29 (1974)</u>	<u>Ref. 8 (1975)</u>
1974	7.65	7.90
1975	7.85	8.45
1976	8.80	10.20
1977	9.25	10.75
1978	9.60	12.05
1979	10.50	13.10
1980	11.40	13.80
1981		16.65
1982		19.20

Nuclear Exchange Corporation has also released estimates of future prices for yellowcake. The unit prices as they appeared in each reference are reproduced below:

<u>Year of delivery</u>	<u>Estimated cost (\$/lb U₃O₈)</u>	
	<u>Ref. 32 (May 1974)</u>	<u>Ref. 33 (May 1975)</u>
1975	11.25	
1977	14.00	
Mid-1977		24.60
Mid 1978		27.05
1979	16.00	
Mid-1979		29.50
1980		31.55
1981	18.25	
1983	19.75	

One U.S. uranium supplier¹¹ says that a price of \$50/lb estimated for 1985 will be on the low side.

REFERENCES

1. ERDA News Release, June 25, 1975, from Public Affairs Office.
2. U.S. Atomic Energy Commission, "The Nuclear Industry 1970," prepared for the Atomic Industrial Forum Conference, Washington, D.C., Nov. 18, 1970.
3. ERDA News Release No. 16, June 27, 1975, from Public Affairs Office.
4. *The Nuclear Industry 1974*, WASH-1174-74.
5. *Nucleonics Week* (July 3, 1975).
6. J. F. Hogerton, "U.S. Uranium Supply and Demand — Near Term and Long Range," *Nucl. News*, pp. 45-50 (May 1975).
7. Emanuel Gordon, "Uranium — New Development Is Targeted at the Future Nuclear Generating Market," *Eng. Mining J.*, pp. 156-60 (March 1974).
8. ERDA News Release No. 33, Sept. 9, 1975.
9. *Nucleonics Week* (Apr. 18, 1974).
10. *Ibid.* (Aug. 21, 1975).
11. *Ibid.* (July 3, 1975).
12. "Colorado's Uravan Mineral Belt Booms Again as in the 50's," *Nucl. Ind.*, pp. 28-29 (September 1975).
13. L.F.C. Reichle, "The Economics of Nuclear Power," presented to the New York Society of Security Analysts, Aug. 27, 1975.
14. Office of Planning and Analysis, United States Atomic Energy Commission, *Nuclear Power Growth 1974-2000*, WASH-1139(74), p. 24 (Feb. 14, 1974).
15. *F.S.V. Progress Report for Period Ending June 30*, GA-A12200 (1972).
16. R. V. Sondermayer, "Thorium — Waiting for Nuclear Fuel Market to Take Off," *Eng. Mining J.*, pp. 196-98 (March 1975).
17. Ann MacLachlan, "World U_3O_8 Going, Going, Almost Gone Says Canadian Geologist," *Weekly Energy Report*, p. 8 (Sept. 29, 1975).
18. J. W. Franklin, "Uranium," *Eng. Mining J.*, p. 108 (February 1960).
19. R. W. Bernick, "Uranium," *Eng. Mining J.*, p. 88 (February 1961).

20. Ibid., p. 91 (February 1962).
21. Ibid., p. 116 (February 1964).
22. Robert Bracklin, "Uranium," *Eng. Mining J.*, p. 125 (February 1966).
23. John Sherman, "Uranium," *Eng. Mining J.*, p. 108 (February 1966).
24. R. W. Bernick, "Uranium" *Eng. Mining J.*, p. 115 (February 1963).
25. John Sherman, "Uranium," *Eng. Mining J.*, p. 129 (February 1967).
26. F. H. Warren and J. J. Steyn, "Uranium Ore: Purchasing on the Long Term," *Nucleonics* 25(4), 31-42 (April 1967).
27. John Sherman, "Uranium," *Eng. Mining J.*, p. 106 (March 1968).
28. Emanuel Gordon, "Uranium," *Eng. Mining J.*, p. 126 (March 1973).
29. AEC News Release No. T505, Oct. 22, 1974.
30. *Nucleonics Week* (May 1, 1975).
31. Ibid. (May 1, 1974).
32. Ibid. (May 30, 1974).
33. Ibid. (May 8, 1975).
34. Ibid. (Aug. 7, 1975).

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