URANIUM ENRICHMENT:
INVESTMENT OPTIONS FOR THE LONG TERM

The Congress of the United States
Congressional Budget Office

NOTES

Except where noted, all dates are expressed in calendar years.

All sums are expressed in 1983 dollars except as noted.

PREFACE

The Congress has already begun to invest in developing advanced processes for producing enriched uranium fuel for domestic and foreign power reactors. As these efforts proceed, the Congress faces major decisions regarding further investment in uranium enrichment--decisions to be made in the context of larger strategic choices for the U.S. role in international nuclear fuel. Choices of technologies are further complicated by a dynamic world market for enrichment services. Once monopolized by the United States, that market has now been made highly competitive by non-U.S. concerns with sizable capacity of their own and more planned for the future.

One consideration in these Congressional decisions is the cost effectiveness of the investment options. At the request of Chairman Pete V. Domenici of the Senate Committee on the Budget and Marilyn Lloyd, Chairman of the House Committee on Science and Technology, Subcommittee on Energy Research and Production, the Congressional Budget Office has analyzed the long-term costs of several technological approaches. In keeping with CBO's mandate to provide objective analysis, the paper offers no recommendations.

The analysis was prepared under the direction of John Thomasian by Gary Mahrenholz and Mollie Quasebarth, of CBO's Natural Resources and Commerce Division under the supervision of David L. Bodde and Everett M. Ehrlich. The authors wish to acknowledge the contributions of Robert Civiak of the Congressional Research Service, John D. Mayer and Jeffrey W. Nitta of CBO, Gene Schmidt and Howard Huie of the Department of Energy, Jim Davis of the Lawrence Livermore National Laboratories, and Alice M. Rivlin, former Director of CBO. Johanna Zacharias edited the manuscript, and Deborah Dove typed the several drafts and prepared the paper for publication.

Rudolph G. Penner
Director

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SUMMARY

The U.S. government supplies a major portion of the enriched uranium used to fuel most of the nuclear power plants that furnish electricity in the free world. As manager of the U.S. uranium enrichment concern, the Department of Energy (DOE) is investigating a number of technological choices to improve enrichment service and remain a significant world supplier. The Congress will ultimately select a strategy for federal investment in the uranium enrichment enterprise. A fundamental policy choice between possible future roles--that of the free world's main supplier of enrichment services, and that of a mainly domestic supplier--will underlie any investment decision the Congress makes.

THE UNCERTAIN ENVIRONMENT FOR DECISIONMAKING

Several important trends and uncertainties complicate that choice.

- **The outlook for nuclear power.** Whether demand for electricity and reliance on nuclear power will continue to grow as they have in the past is unclear.

- **Competition in the world market.** The monopoly the United States once held in the world market for this product has begun to slip--to 60 percent by 1983. Up to now, the United States has sought to dominate the world supply of enriched uranium to assure the peaceful use of nuclear fuels. This goal is made explicit in the Nuclear Nonproliferation Act of 1978, but competition from abroad makes it increasingly difficult to achieve. Mounting competition from non-U.S. enrichment suppliers--relative newcomers to this expanding market--shows clear signs of becoming stiffer.

- **The current technology's high cost.** The process by which the United States has thus far produced enriched uranium fuel--begun after World War II for the weapons program and called gaseous diffusion--is now old. Although the plants have recently been upgraded, they are highly energy intensive and expensive to run, and they promise to become increasingly so.

- **Current overcapacity and oversupply.** At present, the United States and foreign suppliers of enrichment services have more

than sufficient capacity to meet anticipated demand and both suppliers and users have overstocked inventories of enriched fuel. Whether future requirements will warrant sizable investment of federal dollars in new enrichment capacity is uncertain.

- **Pricing.** Federal statute requires DOE to recover from sales the full costs of its enrichment services; foreign suppliers, in contrast, have greater latitude to alter prices to adapt to shifting market conditions. While foreign suppliers now sell enrichment services at prices between $100 and $120 per Separative Work Unit (the SWU is the standard in which these services are measured), the current U.S. charge must be set at $140 per SWU to recover the full cost of processing.

Thus, with many factors likely to influence the world enrichment market, the Congress faces decisions about achieving nonproliferation policy objectives and about investing in future technologies in a highly uncertain market. One important consideration is cost effectiveness--any overall strategy should consider the effects on the federal budget and on the utility companies that purchase uranium enrichment services. To assist the Congress in devising the best enrichment strategy, the Congressional Budget Office has analyzed the cost effectiveness of the principal investment options.

THE FEDERAL ENRICHMENT ENTERPRISE

Utility companies needing enrichment services enter into contracts with DOE. Each supplies DOE with natural uranium feedstock at its own expense. For a fee--at present, the $140 per SWU cited above--DOE processes the uranium feed and returns the enriched fuel to the customer. The total cost to the utility comes to $271 per SWU, when costs of the uranium feed are included. A typical 1,000 megawatt nuclear power plant requires between 80,000 and 120,000 SWUs a year. Translated into the terms of a residential consumer, the total cost of enriched uranium accounts for less than 8 percent of an average household's yearly electricity bill.

The federal government is now contracted with domestic and foreign utilities to supply about 32 million SWUs a year by 1990. But because of power plant delays and cancellations, actual annual demand may fall to roughly 20 million SWUs by that date, rising to only 27 million by the turn of the century. Present U.S. capacity will be able to produce an annual 27.3 million SWUs through the year 2000, or somewhat more than current and likely foreign demand contracts require.

THE TECHNOLOGICAL CHOICES

The DOE now operates three gaseous diffusion plants, one in Kentucky, one in Ohio, and the third in Tennessee. In addition, it has already invested $2 billion in a facility in Ohio that would produce enriched uranium by the gas centrifuge process; this effort may culminate in a stage of technology considerably more refined than its predecessors. Federal dollars also support research in and development of the advanced isotope separation process; this effort is now under way at the Livermore Laboratories in California.

The function of each of these processes is to separate out the relatively heavier U-238 isotope contained in natural uranium and increase the concentration of the lighter U-235 isotope to a point at which the product is usable as reactor fuel. In raw uranium, the ratio of these two isotopes is more than 99 to one; the enrichment process generally increases the U-235 concentration to 3 percent.

Gaseous Diffusion. The gaseous diffusion plants enrich uranium by exploiting the mass differentials of U-235 and U-238 isotopes. The process first converts the natural uranium to a gas (uranium hexafluoride) and then pumps it through several chambers with porous walls. Being lighter, U-235 isotopes pass through the walls more quickly, leaving the heavier U-238 components behind. After several thousand passes through the chambers, the uranium is sufficiently enriched. Substantial electric power is needed to pump the gas through each chamber, resulting in very high operating costs: some 85 percent of this process' cost is attributable to electricity.

Gas Centrifuge. This technology, already in operation abroad and quite far in development in the United States, promises to enrich uranium at substantially lower cost. Like the gaseous diffusion process, this technique separates the U-235 and U-238 isotopes in uranium hexafluoride gas, but it does so more efficiently. The gas is spun in a rotor, and centrifugal force propels the heavier U-238 outward; the lighter U-235 isotope tends to remain in the core of the centrifuge. As in the diffusion processes, enrichment by the centrifuge method requires repeated operations. Nonetheless, the latter uses only 5 percent of the power consumed in gaseous diffusion to produce the same amount of fuel.

For the Gas Centrifuge Enrichment Plant (GCEP) now under construction in Ohio, this technology is being developed in stages, or "sets." The Set IV phase is already nearing completion, and recent advances using different materials have opened the possibility of a Set V technology. This more refined stage, called advanced gas centrifuge (AGC), could double the efficiency of the operation. Though the future costs of the gas centrifuge process, especially those at the Set V stage, are somewhat uncertain, sizable improvements in efficiencies seem possible. Cost estimates now range from between $20 to $80 per SWU (not including uranium feed), with the lower estimates associated with AGC.

Advanced Isotope Separation. Considerably more experimental, this enrichment process uses laser light to separate the isotopes in uranium in a solid rather than a gaseous form. The technique, called the atomic vapor laser isotope separation (AVLIS) process, removes an electron from the U-235 isotope while leaving the others undisturbed. The charged U-235 particles can then be collected separately, affording appreciable enrichment in just one stage. The AVLIS process is estimated to cost between $20 and $30 per SWU, although these figures are uncertain owing to the technology's early stage of development.

INVESTMENT OPTIONS FOR FUTURE ENRICHMENT SERVICES

Planning for future enrichment capacity takes into account both the current availability of gaseous diffusion and the anticipated availability of the new technologies by certain dates. Both DOE and CBO assume different combinations of existing and new enrichment processes when considering an upgraded enrichment enterprise. The technological composition and assumed timetables of five possible courses examined by CBO--a base plan and four alternatives--are recapitulated in Summary Table 1. As its base case, the CBO has taken DOE's recommended program from its most recent operating plan, published in January 1983. In the initial analysis, the CBO has relied on DOE's engineering projections and cost data.

The CBO compared the four options against both the Base/DOE Plan and against each other. The analysis focused on three questions:

- Which investment option would supply the cheapest enrichment service to the consumer?

- Which would cost the federal government the least in direct outlays?

- What effects do alternative demand projections for enriched uranium have on choice of technology?

The projection period examined is 1983 through the year 2025. In its initial analysis, the CBO examined the options with a uniform set of assumptions. Key assumptions include a policy decision to reach annual production levels of 26.5 million SWUs by 1996 to meet a projected high level of demand, attainment of DOE's projected availability schedules for

SUMMARY TABLE 1. COMPOSITION AND TECHNOLOGY TIMETABLE ASSUMED UNDER THE OPTIONS

Options	Gaseous Diffusion	Gas Centrifuge Enrichment Plant	Advanced Gas Centrifuge	Atomic Vapor Laser Isotope Separation
Base/DOE Case	Shutdown of one plant in 1993; remaining two operational through year 2025	Set III machines operational in two buildings by 1988; Set IV machines operating in full eight-building plant by 1997	Not assumed	Not assumed
Option I	Phaseout of all three plants by 1996	Set III machines operational in two buildings by 1988; Set IV machines operating in full eight-building plant by 1997	Not assumed	Two plants in operation as of 1994 and 1995
Option II	Phaseout of all three plants by 1997	Set III machines operating in first two buildings by 1988, to be replaced by Set IV machines in early 1990s; work on remaining six GCEP buildings halted	Not assumed	Three plants in operation as of 1994, 1995, and 1996, producing at full capacity in 1998
Option III	Phaseout of all three plants by 1999	Progress stopped on GCEP plant and project decommissioned in 1983	Not assumed	Three plants in operation as of 1994, 1995, and 1996, producing at full capacity in 1998
Option IV	Phaseout of all three plants by 1999	Set III machines operating in first two buildings by 1988; refined Set IV installed in next four buildings by 1993; AGC (Set V) operating in last two buildings by 1995; all machinery upgraded to AGC level by late 1990s		Not assumed

SOURCE: Congressional Budget Office.

the AGC and AVLIS technologies, and realization of DOE's present cost projections. However, to test the validity of its results from the initial analysis, the CBO also applied less optimistic supply, cost, and schedule assumptions in a sensitivity analysis.

For each option, the analysis examined both federal outlays--that is, annual discounted costs to the U.S. Treasury--and total enterprise costs. The former comprise the costs of delivering enriched fuel, and they include money spent for research and development, capital investment, and operation and maintenance of plants. The latter include these same components plus the price of uranium feed and interest charges on capital.

Results of the Analysis

Several points emerge quite distinctly in the initial analysis. First, the range of total enterprise costs is quite narrow. Over so long a period (43 years), the cost difference of $13 billion between the cheapest and costliest options is not great. Second, the more advanced technologies--AGC and AVLIS--appear to offer the best prospect for an enrichment enterprise with low operating costs. Conversely, prolonged reliance on the costly gaseous diffusion process appears to be the most expensive course, postponing opportunities for lowering enrichment costs. Third, the sensitivity analyses conducted tend to corroborate these findings. Even with their progress slowed and their capital costs inflated by overruns, the more advanced but remote AGC and AVLIS processes appear ultimately to offer the better prospects for a sound long-term investment.

Ranking of the Options on Three Standards. The analysis results in the following ranking of options. In terms of total enterprise costs, Option IV, ultimately relying on AGC for enrichment services, would offer the most economic approach, with costs over the full projection period totaling $123.5 billion (see Summary Table 2). Option III, ultimately relying on AVLIS without GCEP or gaseous diffusion, falls next in the sequence, with enterprise costs of $128.2 billion. Options I and II, involving combinations of the gas centrifuge and AVLIS technologies, follow closely with enterprise costs of $128.7 billion and $129.6 billion. At the bottom of the ranking and markedly more expensive than the other options is the Base/DOE Plan, with enterprise costs of $136.8 billion over the projection period.

Total government outlays over the same period, also shown in Summary Table 2, follow the same pattern. The Base/DOE Plan would require the greatest outlays ($41.4 billion), while building Option IV would require the least ($28 billion). However, the schedule of outlay trends differs over the period 1983 to 2025. Through 1990, Option IV would require $18 billion

SUMMARY TABLE 2. SUMMARY OF DISCOUNTED COSTS AND OUTLAYS UNDER EACH OPTION 1983-2025

	Base/DOE Plan	Option I	Option II	Option III	Option IV
			Discounted Enterprise Costs in Billions of 1983 Dollars		
Gaseous Diffusion	90.9	46.6	53.7	58.5	44.8
Gas Centrifuge a/	45.9	45.9	15.1	1.4 b/	78.7
AVLIS	None	36.2	60.8	68.3	None
Full-Period Total	136.8	128.7	129.6	128.2	123.5
1983-2003 Total	87.4	85.3	86.2	85.4	82.3
			Discounted Federal Outlays in Billions of 1983 Dollars		
1983-1990	17.9	18.7	16.9	15.2	18.2
1991-2000	11.3	10.1	12.1	13.1	7.8
2001-2025	12.2	4.3	5.1	4.7	2.0
Full-Period Total	41.4	33.1	34.1	33.0	28.0
			Costs per SWU in 1983 Dollars		
Full-Period Total Fuel Cost	129.4	121.7	122.6	121.3	116.8
Full-Period Enrichment Charge	39.4	31.6	32.5	31.3	26.7

SOURCE: Congressional Budget Office.

a. Through Option III, data reflect costs and outlays associated with GCEP operation through Set IV technology; include AGC costs and outlays for Option IV only. Because AGC is the culmination of the GCEP project, its associated costs and outlays are not identified separately.

b. Cost to decommission GCEP project.

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in outlays, roughly equal to the Base/DOE Plan's requirements over that period. Option III, however, would require only $15 billion in capital costs through 1990.

The analysis also indicates that the Base/DOE Plan and all the alternatives would provide relatively low-cost enrichment services as judged by current enrichment prices. All projected enrichment charges would gradually fall well below the current DOE rate of $140 per SWU. If foreign suppliers hold SWU costs at the current levels of $100 to $120 per SWU, the United States would be in a position to compete favorably. As is the case with full enterprise costs, Option IV offers the lowest enrichment charge, $27 per SWU, and the Base/DOE Plan the highest, $39 per SWU.

Sensitivity to Changed Assumptions. Even with changed analytic assumptions regarding the timing of availability and level of demand, the initial rankings hold; although the absolute costs of the options rise. The Base/DOE Plan remains the most costly, while Option IV is the cheapest. When capital cost overrun factors are assigned to the new technologies, the initial rankings remain in all instances but one. The exception involves raising capital costs for AGC beyond current estimates, but using the current estimates for AVLIS. In this instance, Option III becomes $2.0 billion cheaper than Option IV.

The initial ranking holds when the production plans are assumed to be scaled back to meet little more than domestic demand only. In this case, the United States would build to meet demand of 19.6 million SWUs a year instead of 26.5 million after the year 2000. In this situation, Option IV remains the most economic approach, with $93.4 billion in enterprise costs. Again, Option III falls next, involving roughly $96 billion in enterprise costs. The Base/DOE Plan is still the most expensive, with enterprise costs of $99 billion.

In a similar test, the United States is assumed to build full capacity for 26.5 million SWUs but eventually to service only domestic demand and existing foreign contracts--that is, to produce only 19.6 million SWUs a year after 2000. Again, the ranking of the options holds. Option IV is the most economic, while the Base/DOE Plan is the least so. Though the lifetime cost per SWU under Option IV rises from $27 to $32, it remains well below current world prices. These and other sensitivity analyses performed by CBO suggest that, although technical and economic uncertainties do exist regarding the advanced processes, investment in the GCEP facility carried through the AGC stage offers the United States the most cost-effective production plan for sustaining competition in the uncertain uranium enrichment market. At the same time, the overall cost difference between this lowest-cost option and the next best choice--Option III using AVLIS--remains strikingly small.

URANIUM ENRICHMENT:

Investment Options for the Long Term

CHAPTER I. INTRODUCTION

Enriched uranium, much of it processed under the management of the U.S. government, fuels most of the world's nuclear power plants. These plants are the source of between 12 percent and 15 percent of the electricity consumed in the industrialized free world. In the United States, where the Department of Energy (DOE) undertakes all uranium enrichment activity, 13 percent of all electrical energy is produced by uranium, and in several other nations, reliance on nuclear energy is somewhat greater. Thus, the demand for enriched uranium is already sizable, and although the outlook for future energy growth is unclear, that demand is expected to remain large and possibly to grow in the coming several decades. Critical to the United States' future position in the world enrichment market are decisions now before the 98th Congress concerning federal investment in uranium enrichment technologies.

THE U.S. POSITION IN THE WORLD MARKET

What share of the free world's demand for enriched uranium will be met by the United States is uncertain. From 1969 through the 1970s, the United States held a commanding position as the principal provider of enrichment services. Since the late 1970s, however, the United States has been losing its market dominance as other countries have introduced their own enrichment capacity. While the United States still services almost all domestic enrichment demand, it supplies less than 60 percent of the current foreign market demand. Contracts now in effect indicate a continuation of this downward trend, and the U.S. share of foreign markets is expected to fall to less than 35 percent over the next ten years.

THE FEDERAL ENRICHMENT ENTERPRISE

As the nation's sole provider of uranium enrichment services, DOE controls and promotes these activities in accordance with national policies for control of nuclear materials (further considered in Chapter II). At present, the federal government aims to hold a dominant role in the world market to monitor the nuclear fuel cycle and thereby prevent nuclear materials from being diverted for use in weapons. The mechanism by which this service is provided is simple enough. Utility companies needing enriched uranium to fuel reactors supply DOE with unprocessed uranium