

Supplying enriched uranium

Unless government and industry can move together quickly to construct modern enrichment plants, US utilities face a shortage of enriched uranium fuel.

Vincent V. Abajian and Alan M. Fishman

Among the problems that must be solved before nuclear power can finally become a mature industry providing a major fraction of the nation's electric power, perhaps the least publicized is the problem of making sure there will be enough enriched uranium to fuel the rapidly growing numbers of nuclear power plants. Currently there are 29 nuclear plants generating 15 000 megawatts, or less than 5% of the nation's total capacity; by 1990, the AEC predicts that the nuclear plant capacity will have grown by more than a factor of 40 and will be roughly half of the total national capacity.¹ Unfortunately, no plans have been made for a parallel expansion in the country's uranium-enrichment facilities that must supply the fuel for all these new plants.

Unlike fossil fuel such as coal or oil, uranium fuel must undergo complicated processing (see figure 1) before it is ready to be fed into a power plant. An essential step (which accounts for about 1/3 of the total fuel-cycle cost) in this processing is the enrichment of newly mined uranium from its natural concentration of 0.7% U^{235} to a concentration of 2–4% U^{235} . Currently, all enriched uranium is produced by three government-owned facilities that were built 15–25 years ago. The nuclear power industry's needs for enriched fuel will soon outstrip the combined capacity of these plants.

Unless new enrichment facilities can be brought into operation in the early 1980's, the expanding nuclear power program, which is our main hope of offsetting the growing oil shortage, will be faced with a fuel shortage of its own. The Atomic Industrial Forum and others in the nuclear industry have

expressed concern that it may already be too late to head off this shortage.² They question whether enough time remains to plan, construct and put new plants into operation by the dates they will be needed.

The circumstances that have created this problem have to do with the fact that the separation process is the only part of the nuclear fuel cycle that is still entirely in government hands. Historically, AEC has, for reasons of national security, insisted on both heavy classification of information about separation processes and retaining direct control over any processing plants. The argument has been that these precautions were essential to prevent the proliferation of facilities capable of producing weapons-grade enriched uranium.

A second reason why enrichment has remained a government monopoly is the enormous investment needed to build enrichment plants. The three existing government plants cost of the order of \$2 billion.

About two years ago the government reversed its position and decided that the private sector should become involved in the enrichment business and in particular that private industry should take over the responsibility of owning and operating any new enrichment facilities that are built. However, private interests, just beginning to puzzle out the economics of the business and uncertain about how government decisions might influence the long-range future of this new market, have so far not volunteered to take over the responsibility offered by the government. This situation, then, explains why no new enrichment plants are under construction, in spite of the obvious need for them.

A big factor contributing to the economic uncertainty is the question of

whether the particular method of enrichment (gaseous diffusion through porous barriers) used in the AEC plants should be abandoned in any new plant built in favor of a method that uses high-speed centrifuges to perform the enrichment.

Before deciding on capital investments that will provide the foundation for what will become a \$5-billion-a-year industry by the year 2000, private interests will need time to reach conclusions about the economic potential of the centrifuge method compared to the older diffusion method.

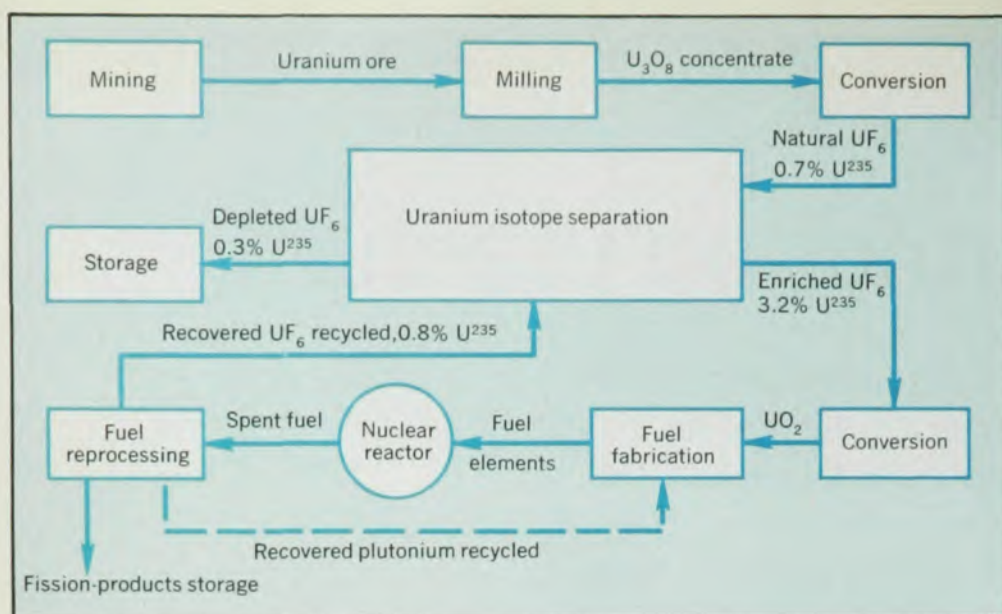
On the other hand, the urgency of making these investments is increased by still another consideration—the possibility that foreign competitors might move to take over a large share of the enrichment business. For the last two decades the AEC has been essentially the sole source of enriched uranium not only for the US but for the entire non-communist world. But recently, a European consortium has been formed to build enrichment plants on European soil and already has three pilot plants under construction. It would be a serious blow to the US balance-of-payments situation if this country failed to retain its position of major supplier of enriched uranium in the coming age of nuclear commercial power. Both private and government interests agree on the importance of moving quickly to meet the challenge being posed by foreign interests in enrichment.

In the following we will first review and compare the two competing enrichment processes (diffusion and centrifuge) and then discuss more generally the difficulties facing private industry's entry into the enrichment business.

Status of enrichment technology

Currently only gaseous diffusion and

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Processing cycle for uranium fuel supplied to nuclear-fission power reactors. Cost of enriching U^{235} content accounts for one third of total fuel-cycle cost. Figure 1

gas centrifugation are being considered for large-scale separation of uranium fuel material. With either of these processes, the separation that can be achieved in a single application of the technique is small. Therefore, to separate feed material at a particular concentration into fractions at substantially different concentrations, repeated application of the technique is required. This is most efficiently accomplished in assemblages of the separation devices called "cascades," through which the separated fractions flow countercurrently.

Gaseous diffusion. In the 1940's the government decided to develop the gaseous diffusion barrier process for large-scale enrichment in which separation of U^{235} and U^{238} is achieved by taking advantage of the slightly different diffusion rates of these two isotopes through porous barriers (see box, page 25). For the last thirty years this process, now highly developed, has been used by the AEC to produce virtually all of the enriched uranium made in the non-communist world.

Presently the combined diffusion plant capacity for the non-communist world exists at five plants as shown in Table 1. Figure 2 is a view of the most massive plant yet built. This complex, located in Paducah and originally built in 1954, consists of 30 buildings, covering 74 acres and cost \$791 million to build.⁴ The plant circulates 500 million gallons of water per day for process purposes. The total US gaseous diffusion complex of 17 200 000 SWU/yr requires 6000 MWe of electricity when operated at full capacity. This is enough power to satisfy the combined needs of the people of Philadelphia, San Francisco and Denver, or the entire state of Minnesota.

Gas centrifuge. Any plans for installing new enrichment capacity must

give serious consideration to the gas centrifuge as a potential competitor to the established diffusion process. Application of the gas-centrifuge process for uranium separation dates back to World War II, when long-bowl, rigidly supported gas centrifuges were tested by the US as a possible alternative to the gaseous-diffusion method for isotopic separations. They were found unsuitable, and interest in the centrifuge as a means of separating isotopes waned until the late 1950's, when an Austrian scientist, Gernot Zippe, took a completely new approach toward the construction of centrifuges.⁵ Zippe's design, (see box, page 25) basically similar to a spinning top, bottom-supported with a vacuum casing, was of light-weight construction (as contrasted with the then conventional top-suspended heavy centrifuge machinery). Consequently, centrifugal stresses and power consumption were reduced while higher peripheral speeds were obtained.

Zippe's report describing his accomplishments, issued in 1960, was the last unclassified publication on gas-centrifuge technology released in this country. Advances in the technology beyond Zippe's published material have been shielded from public view through strict security measures both in Europe and the US. However, the broad outlines of development programs have been made public.

In the Spring of 1970, the UK, West Germany, and the Netherlands signed a trilateral agreement pooling their research and development in centrifuge technology looking towards joint construction of large-scale gas centrifuge enrichment plants beginning later in this decade.

The front cover shows a British gas-centrifuge plant being erected at Capenhurst, where old gaseous-diffusion stag-

es are being removed and replaced by centrifuges. A number of cascades, each with several hundred centrifuges, are expected to be fully installed this summer.

By the fall of 1974, the tripartite group expects to have three pilot plants in full operation totalling about 90 000 SWU/year capacity and probably containing more than 10 000 production-type centrifuges.²

In the US, gas-centrifuge research and development funding has been increasing dramatically.⁶ The AEC has utilized Union Carbide Corporation and the Garrett Corporation (Division of Signal Oil) as the major contractors for its program. Electro-Nucleonics, Inc also has an AEC prime contract for the conduct of development work on various centrifuge components and subsystems.

The AEC recently reported that some early model centrifuges ran continuously for more than eight years, while some advanced design machines now undergoing tests have logged five years to date. The Commission is constructing a pilot plant to demonstrate the gas-centrifuge process, called the Component Test Facility (CTF) on a budget of \$21 million. This plant, due to start up in FY 1975, will have a capacity appreciably greater than the 25 000 SWU/year capacity of the Dutch centrifuge plant at Almelo, Netherlands, the first of the European plants to go into operation. The advanced-design centrifuges to be installed in the CTF are believed by the AEC to be potentially capable of competing with gaseous diffusion, and FY 1976 is considered the target date for an economic assessment of the two processes.

In Japan, the Power Reactor and Nuclear Fuel Development Corporation (PNC) is pursuing a research and development program in gas centrifuges, including plans to build and operate a centrifuge cascade consisting of 180 machines stacked in 13 stages for the enriching section and five stages for the stripping section. Before the end of the year the Japanese may decide to go ahead with a complete centrifuge enrichment facility estimated to cost \$325 million.

Development funding for each of the above three national efforts is now approximately the same, \$20 million/year.

Process comparison

Although a detailed comparison between the centrifuge and diffusion processes is not possible because of security limitations, we can summarize the reasons why many feel the centrifuge looks more attractive than the diffusion barrier for future enrichment plants. In the last analysis, the pro-

How the enrichment processes work

The effort involved in separating isotopes, referred to as the "separative work," is proportional to the product of two factors: L , the flow through the separating device, and $(\alpha-1)^2$, where α is the separation factor for the device. Separative work is measured in separative work units (SWU). Following are the basic principles involved in the two competing enrichment processes: **Gaseous diffusion.** Separation by gaseous diffusion takes place because the lighter molecules in a gaseous mixture move faster than the heavier molecules and will, therefore, strike the container walls more often. If the walls have holes of the right size, relatively more light molecules will escape. The best separation that can be achieved in one application of this process is $\alpha = (M_2/M_1)^{1/2}$ where M_2 and M_1 are the molecular weights of the isotopic compounds involved. For UF_6 molecules, the only practical gaseous form of uranium, $\alpha = 1.00429$. Thus $(\alpha-1)$ is small and L must be large to achieve a given overall separation. In consequence, gaseous-diffusion plants tend to be large.

Unless the gas that gets through the wall or "barrier" is kept at a lower pressure than the original material on the

other side, it will just as readily go back to its original location and no separation will occur. Consequently, a great deal of pumping of gases has to be done throughout a gaseous-diffusion cascade. This pumping consumes power and generates heat. The figure shows a typical gaseous-diffusion stage. A diffusion plant consists of thousands of these stages.

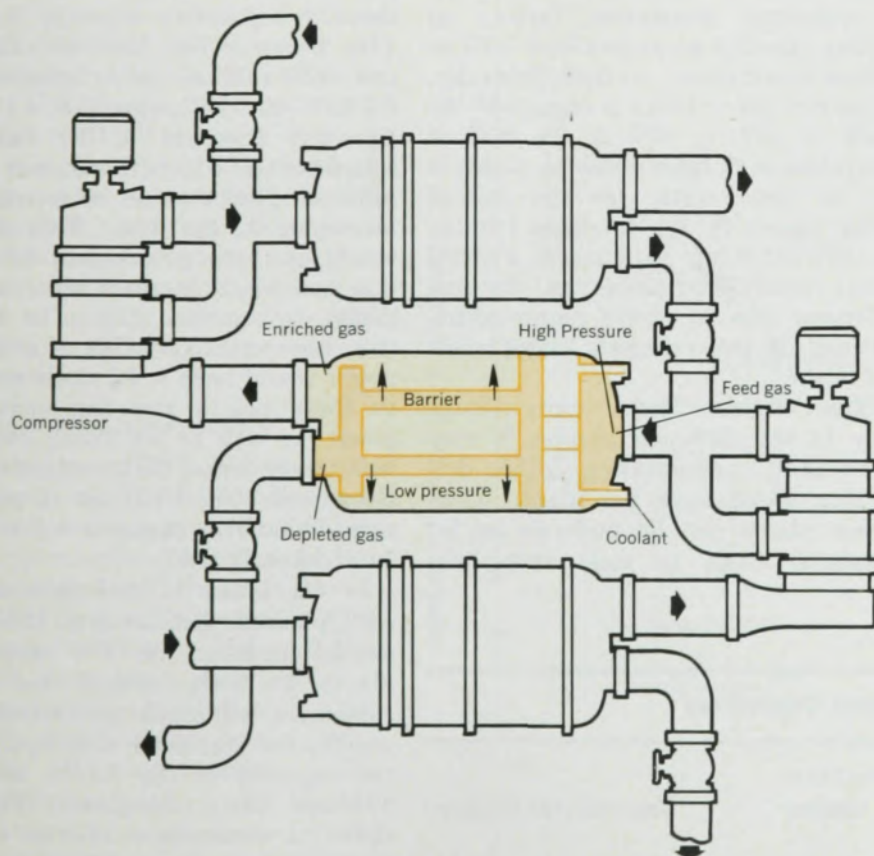
High-speed centrifuge. The centrifuge works on the principle that in a rotating cylinder the centrifugal force tends to compress the gas molecules in the cylinder to the outer radius (see figure). However, the thermal velocities of the molecules tend to keep the gas molecules evenly distributed throughout the available volume. Since the latter effect is larger for the lighter molecules, there are relatively fewer lighter molecules at the outer radius. The average concentration of the content is achieved at some intermediate radius, which gets closer to the outer radius as the speed of rotation increases. The centrifuge has a relatively large separation factor but a smaller flow rate than a diffusion stage. For a centrifuge operating isothermally, the maximum separative capacity of the machine is:

$$\delta v_{(\max)} = \pi \rho D (Z/2) (\Delta M V^2 / 2RT)^2$$

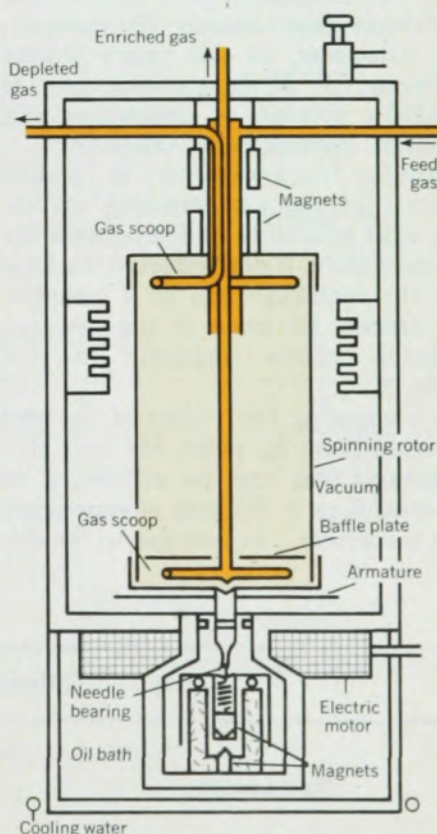
- δv = separative work
- Z = bowl length
- V = peripheral velocity
- T = absolute temperature
- ρ = gas density
- D = diffusivity
- ΔM = isotopic mass difference
- R = gas constant

Note that the separative effect is proportional to the difference of the masses of the isotopes rather than the quotient as for gaseous diffusion. The centrifuge separative-work equation also indicates the desirability of operating at a low temperature with a long bowl at high peripheral speeds.

Gernot Zippe published results in 1960's with centrifuges approximately one foot long, spinning at 350 meters/second at a temperature of 33°C. These parameters yielded separation factors of 1.1-1.2 (compared to the maximum for diffusion of 1.004). Thus, only relatively few centrifuges need be connected in series to achieve substantial changes in concentration. However, since flow rates possible in centrifuges are much lower than diffusion stages, large number of centrifuges in parallel are required for practical levels of throughput.



Typical gaseous diffusion stage in enrichment plants now operated by AEC.



Gaseous centrifuge stage, see ref. 5.



Paducah gaseous diffusion plant built and operated by the AEC since 1954 covers 74 acres and consumes 2550 Mw of power when functioning at full capacity. Figure 2

cess that can produce enriched uranium at the lowest cost will win. Presently, it appears that centrifuge plants may already be economically competitive with diffusion plants. This is indicated in a comparison summary published last year in an Atomic Industrial Forum study² and reproduced here in Table 2. [Unfortunately, precise detailed cost information has still not been declassified by the AEC, which is one factor for the delay in serious planning on the part of the industry (see box, page xx).]

So far the AEC has declined to endorse the conclusion of Table 2 that centrifuges may already be competitive. However, in this year's budget testimony,⁶ F. P. Baranowski, director of AEC's division of production and materials management, observed "... continuing improvements in performance and the accumulating experience with reliability and productibility to date justify, if not reinforce the view that the centrifuge can be a competitive process for some of the new enrichment plants required in the 1980's."⁶

In comparing the merits of the two processes point by point, the only disadvantage that can be attributed to the centrifuge is the lack of experience with the process. In contrast to the dif-

fusion process, which has accumulated many years of successful operation, no large-scale centrifuge plants have been operated. As a result there are no proven figures on component reliability and maintenance and replacement costs. On all other points of comparison however, the advantage appears to lie with the centrifuge, either in terms of potentially lower costs or other considerations, as follows:

Power consumption. Power consumption of a full-size diffusion plant is so great that a separate electric power plant is required to operate it. A centrifuge separation facility of similar capacity consumes only 10% to 15% as much power, so that, generally, no special power plant is required. As much as 40% to 50% of the cost of separative work from diffusion plants is due to power costs. As the cost of power begins to rise (perhaps tripling by 1990 according to a recent Federal Power Commission projection) the cost difference due to power requirements between the two processes looms larger and larger.

Effect of size. The economy of large scale in the diffusion process is very pronounced, necessitating billion-dollar-plus investments per plant. Centrifuge plants can be built on an incremental basis to meet rising de-

mands. This reduces risks and allows advances in technology to be incorporated into plant additions.

Learning curve. Centrifuge development work has only been carried on in earnest for a decade. Greater improvement can be expected for the centrifuge process than for the older, more mature diffusion process.

Environmental impact. Since the centrifuge uses less power than the diffusion process, centrifuge plants should have a less adverse effect on the local environment. Also, since inventories of the UF_6 process gas in a centrifuge cascade are considerably smaller than in a corresponding diffusion cascade, the centrifuge cascade presents a much smaller potential hazard in the extremely unlikely event of an accident in which process material escapes.

Planning for new capacity

The inexorably rising demand for enriched uranium is expected to surpass the existing US diffusion capacity by 1977. However, to postpone the date when new facilities will be required, the AEC proposes to continue to reproduce and stockpile enriched material. The AEC also proposes to spend considerable funds to improve the performance of its 15-25-year-old plants. The Cascade Improvement Program (CIP) involves installing improved diffusion barriers.⁴ This would increase the US separative capacity by 33%. This program has been estimated to cost \$630 million and is scheduled for FY 1976-80. Following CIP, a Cascade Upgrading Program (CUP) has been scheduled in which the output of the diffusion plants would be increased by increasing its gas flow. This program would cost the government \$220 million and would increase separative capacity by another 21%. To achieve this, however, 1330 MWe of additional power would have to be made available to these plants and the shortage of power as well as its rising cost may well diminish CUP's attractiveness. Even with CIP/CUP, it is generally agreed that new capacity will be needed in the early 1980's.

In its latest official forecast, the AEC predicts that the most likely total annual demand on US enrichment plants, for both domestic and foreign customers, will reach 124 700 000 SWU/year by the year 2000; that is, 4.5 times the capacity of the AEC's improved diffusion plant complex.¹ Figure 3 shows a comparison of the demand projections (high, most likely and low) with the currently authorized but not yet completely implemented, increases in capacity. Demand exceeds supply around 1981, so that additional capacity must be brought on stream—or shortly thereafter (preproduction and operation of the diffusion plant at

Table 1. Diffusion Plant Capacities

Plant Location	Country	Capacity (10^6 SWU/yr)
Oak Ridge, Tennessee	US	4.7
Portsmouth, Ohio	US	5.2
Paducah, Kentucky	US	7.3
Capenhurst	UK	0.4
Pierrelatte	France	0.2*

* Estimated, actual capacity classified³

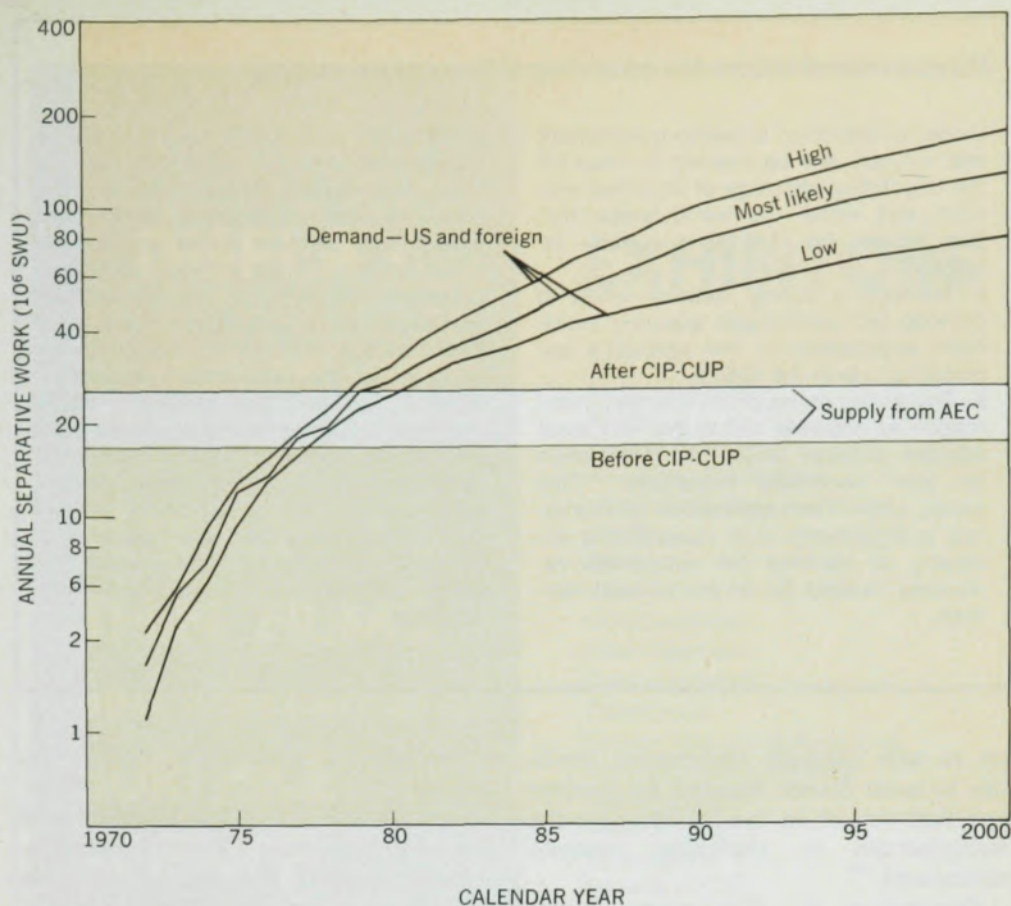
higher than optimum tails assay can postpone the crossover dates for a few more years, but those manipulations are neglected here).

Additions in capacity to match growth in demand can be accomplished in many ways, but, for illustrative purposes, figure 4 indicates two possible approaches. At the upper portion of the figure, a scheme using diffusion plants is shown; plants of capacity 8 750 000 SWU are added each time the most likely demand threatens to exceed the supply existing at that time. With this scheme, eleven diffusion plants are needed between 1981 and 2000, or about one plant every 1.7 years. The lower part of figure 4 shows a scheme whereby centrifuge plants of capacity 2 000 000 SWU are added each time the most likely demand threatens to exceed the supply. (The 2 000 000 SWU capacity was selected to make the additions visible on the graph and to correspond to a reasonable number of plants. Smaller plants, with closer approach to the demand curve, and therefore, smaller excess installed capacity could also be used with very little, if any, increase in the unit cost of the separative work.) Thus 48 centrifuge plants would be needed between 1981 and 2000, or about one plant every five months.

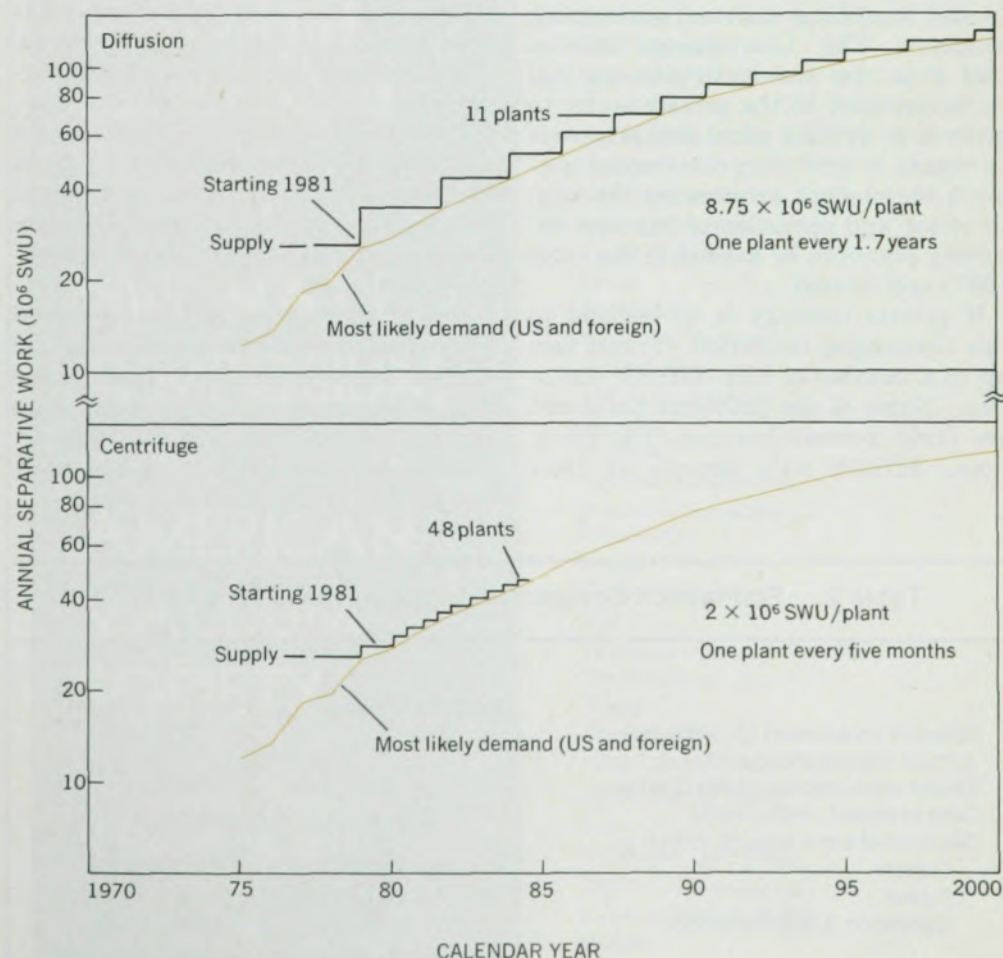
Obviously, the diffusion plants, which must be constructed in large sizes to achieve low unit cost of separative work, require greater excess installed capacity than do the centrifuge plants. The eleven diffusion plants might not need eleven new sites, of course, and the 48 centrifuge plants need not require 48 independent sites either, but the centrifuge plants could be more widely distributed or more convenient locations, with obvious advantages in logistics, national security, business competition and customer convenience.

Problems of private ownership

Reversing its earlier policy of prohibiting private industrial involvement in enrichment technology, the AEC recently implemented an Industrial Participation Program in Uranium Enrichment. The seven companies continuing through a two-step AEC selection procedure have been given access to the Commission's classified technological information in both gaseous diffusion and gas centrifugation. (The seven companies selected were Electro-Nucleonics, Exxon Nuclear, General Electric, Goodyear Tire and Rubber, Reynolds Metals, United Aircraft and Westinghouse Electric.) The companies were granted approval to conduct independent research and development programs in either technology with the view towards, as the Commission states, "the investment by indus-



Uranium enrichment capacity. Demand versus supply in terms of total annual separative work as a function of year. Based on information in WASH-1139 (72). CIP-CUP refers to AEC program to upgrade existing diffusion plants. Tails at 0.3%. Figure 3



Enrichment-plant additions to match demand. Comparison of diffusion plants (top) with centrifuge plants (bottom) shows latter match demand curve more efficiently, since, unlike diffusion plants, centrifuge plants can be built in small sizes. Figure 4

Recommendations for ensuring US uranium supply

Closer cooperation between government and industry will be needed to head off the impending shortage of enriched uranium and retain US world leadership. Specifically the following would be helpful:

- ▶ Maintain a strong, national effort to develop gas centrifuges assuring maximum exploitation of the process's potential for use in the 1980's.
- ▶ Declassify as much enrichment information as possible and at the very least release detailed economic information on both candidate processes. This would allow freer exploration of financing arrangements with investors, a necessity to harness the substantial resources needed for an enrichment venture.

▶ Establish guidelines by the Justice Department and the AEC with respect to the application of anti-trust law and policy to new commercial enrichment enterprises, so that those companies who have an interest in enrichment can determine whether or not a proposed venture would be favorably received.

▶ Encourage utilities to take an active interest in the enrichment business. Utilities should make long-term commitments in advance for enriched fuel and should consider making capital investments in new commercial enrichment plants. Utility ownership of enrichment plants, either on a cooperative basis or individually for the smaller-capacity gas-centrifuge plant, also merits attention.

try in new uranium enrichment facilities to meet future demand for nuclear and fuel and/or in the facilities for the manufacture of enriching systems equipment."⁷

Expanding on this view, James Schlesinger, former AEC Chairman, made the following statement⁸ on 7 March 1972: "Both the President and the Commission have expressed the view that private industry should in the future assume responsibility for providing uranium enrichment capacity and furnishing uranium enrichment services. The Commission believes that it is now timely to give our full encouragement to the private sector to proceed to develop plans and proposals to engage in providing commercial uranium enrichment services by the construction and operation of the new enriching plants to be needed in the early 1980's and beyond . . ."

If private industry is to respond to this challenging invitation, it must face up to a number of very difficult obstacles. Some of the problems presented are fairly normal business-type situations, difficult only because of their

unprecedented magnitude; others are unique.

First are the interrelated problems of financing and risk. The financial requirements for a new gaseous-diffusion enrichment plant are of the order of a billion dollars, suggesting the likelihood that some type of industrial joint venture will be involved. The viability of the financial structure will almost certainly depend upon the willingness of the utility industry to enter into firm long-term commitments for enriched fuel that will assure the revenues required to meet debt obligations. The financing problem is further aggravated by the requirement for electric power facilities in the instance of a diffusion plant—a further investment of about \$700 million—that also would undoubtedly require a firm long-term commitment on the part of the enrichment enterprise.

Potential investors will be concerned with risks threatening the commercial success of the enterprise. There is the risk of government competition, since the government may very possibly decide to continue the commercial oper-

ation of its three soon-to-be-improved enrichment facilities with their substantial cost advantages. There is the risk of a falling off of the foreign market, representing about 40% of the projected requirements for 1981, as a result of foreign technological advances or foreign government subsidization.

Perhaps most serious in the case of a gaseous-diffusion plant is the risk that the plant may become non-competitive with newer plants using a more advanced and more economic technology. A number of these problems and risks would be eliminated or minimized if further development and successful demonstration should lead to commercial application of the gas-centrifuge process. This is largely the result of one factor—the smaller plant size feasible with centrifuges. This factor allows a much greater flexibility in choosing the optimum size of the plant, reducing financing requirements and financial risk. In addition, since the gas-centrifuge process requires a power supply of only 10% to 15% of the gaseous-diffusion requirements, the power-supply problem is largely eliminated.

A second significant problem area arises from the legal requirement that private enrichment plants must obtain construction permits and operating licenses from the AEC. The questions of radiological health and safety and environmental impact, normally the principal subject of the AEC licensing review, should be of less significance for an enrichment plant than for a nuclear power plant. The exception is that electric generating facilities required for a gaseous-diffusion plant would, of course, present the usual environmental-impact difficulties. Since the enrichment plant will presumably utilize classified technology, the licensing process here will also have to involve scrutiny of the methods proposed for safeguarding classified information and imposition of regulatory safeguard requirements.

In the case of an enrichment plant, however, the most troublesome aspect of the AEC licensing process may very well be the antitrust review that is required by Section 105(c) of the Atomic Energy Act. The AEC must obtain the advice of the Justice Department on the anti-trust aspects of the proposed activity, and is authorized to deny a license or impose such conditions as it determines appropriate to foreclose conduct inconsistent with the anti-trust laws.

This too is a problem that would probably be minimized for the gas-centrifuge process. With the expected flexibility in plant size and the possibility of entering the field with a significantly smaller capital investment, there could be a relatively large num-

Table 2. Economics Compared for Enrichment Processes

	Gaseous diffusion	Gas centrifuge
Specific investment (\$/SWU/yr)	120-130	120-150
Annual capital charge (%)	15	20
Power consumption (kWh/SWU)	2050-2400	300-400
Cost of power (mills/kWh)	8-9	8-9
Separative work cost (\$/SWU)		
Capital	18.00-19.50	24.00-30.00
Power	16.40-21.60	2.40-3.60
Operation & maintenance	1.50-2.00	4.00-6.00
Cost of separative work (\$/SWU)	39.90-43.10	30.40-39.60

ber of enrichment plants and wide diversity in ownership leading to an incentive for technological improvements and for effecting economies in operation.

Finally, there is the threat of foreign competition. On the occasion noted previously, Schlesinger observed,⁸ "We are currently witnessing, in many countries of the world, efforts directed toward the development of a commercial uranium enriching business and we believe that the normal commercial incentives of our domestic private industry will enhance the competitive position of this country in this world market for economic benefits both to the US as producer and to our customers abroad."

More specifically, the efforts abroad he refers to include: the European tripartite group expecting to have 2000-3000 tons of centrifuge capacity on-line by 1980; the French pursuing a course that would lead to the erection of European gaseous diffusion plants based on their technology, and the Japanese aggressively exploring both technologies. Even the Russians are beginning to enter the world enrichment picture by offering enrichment services to a number of Western European countries.

Undeniably, these activities threaten the financial return that can be expected on private US investments in enrichment facilities. However, this is one challenge that private industry cannot, in our national interest, fail to risk. As history has shown, American industry has the capability and ingenuity to take on complicated technological problems such as uranium enrichment. However, time is short and only early attention to the problems presented in this article by all parties concerned can assure success.

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