Using lasers to create nuclear fuel

A review of the U.S. isotope separation program, by Marjorie Mazel Hecht

When the Manhattan Project was still a top secret during World War II, one of the most daunting tasks scientists faced was how to produce several pounds of fissionable uranium fuel for the atomic bomb. Only traces of uranium-235, the fissile variety of uranium, are found naturally; 99.3% of all uranium is the nonfissionable uranium-238. Although scientists had separated the U-235 isotope in the laboratory using the mass spectrograph, they had produced only thousandths of grams of it. Now they had to devise a commercial-scale technology that would increase the concentration of U-235 to about 90%.

The crash program organized by the government proved equal to the task. With incredible speed and secrecy, the Manhattan Project constructed a huge, half-mile-long gaseous diffusion isotope separation plant in Oak Ridge, Tennessee. This method of isotope separation required enormous amounts of electrical energy, 2,700 megawatts, and therefore, the Tennessee Valley Authority site, with its abundance of electrical energy, was chosen for the plant. Four power plants were constructed at the Oak Ridge site, and the plant's initial power consumption equalled that of the entire Soviet Union in 1939. Two other methods of isotope separation were also explored, the gas centrifuge and electromagnetic separation (the calutron). By March 1943, the task was successfully completed and there was enough enriched uranium—that is, with 90% U-235—to make the first atomic bomb, most of it coming from the calutron.

Today, more than 40 years later, the same gaseous diffusion process is still used to produce the fuel for nuclear power plants as well as weapons, despite the system's inherent inefficiency and vast energy requirements. However, an advanced technology in isotope separation promises to cut the total costs of the process by *two-thirds*. This spin-off of the U.S. laser fusion program has just been selected by the Department of Energy as its next-generation uranium enrichment technology for development. In June, the department gave the green light to Lawrence Livermore National Laboratory to proceed with development of the Atomic Vapor Laser Isotope Separation system, known as AVLIS. The lab is already getting excellent results with the AVLIS laser system using a small, existing separator called Mars, and expects to have a new commercial-size separator working with AVLIS during 1986-87.

The applications of this new laser isotope separation technology are mind-boggling in scope. Laser isotope separation is to industrial materials what genetic engineering is to agriculture—an incredible technological tool to increase productivity and efficiency, moving man into the 21st century. In the nuclear industry alone, isotope separation could tailor materials for the reactor wall that could better withstand neutron bombardment and thus make the wall more durable.

Isotope separation could also be used to "cleanse" nuclear waste, transforming it into valuable heavy metal and gas isotopes, leaving only a minute quantity of highly radioactive material to be disposed of. Both applications would revolutionize the nuclear industry and the coming fusion power industry.

Although enrichment of uranium is the primary job of AVLIS, the same facility can be used to produce other valuable isotopes, both radioactive and stable. Currently, certain of these isotopes are enormously expensive. For example, in 1982, palladium and rhodium, which are used in the catalysis process to turn crude oil into gasoline, cost $900 per ounce and $6,000 per ounce, respectively.[1] They are found naturally only in the Soviet Union and South Africa, but with an inexpensive isotope separation process they could be "mined" from radioactive wastes. Other isotopes are even more expensive. For example, 40% enriched xenon-124 is $90,000 per liter; 0.5% enriched krypton-78 is $20,000 per liter.[2]

At this point, the applications of isotopes are limited only by the ability to produce them inexpensively and in quantity. With the commercialization of the AVLIS technology, industries will have a plentiful and inexpensive source of radioisotopes and stable isotopes.

After the war, the United States led the world in uranium enrichment, supplying the defense industry and later the commercial nuclear power industry using the facilities built during the Manhattan Project. The Atoms for Peace program launched by President Eisenhower in 1953 mandated a U.S. effort to spread this cheap, clean, and efficient power source throughout the world, and hopes were high that the use of nuclear energy would be able to bring the rest of the world up to U.S. living standards and better.

As more nuclear plants came on line here and in other countries, the United States expanded its uranium enrichment capability, based on projections of a 7% to 8% growth rate in electric power consumption. Under the Atomic Energy Act of 1954, the government is the sole supplier of enriched uranium domestically, and the Department of Energy is authorized to sell it for "recovery of the government's cost over a reasonable period of time." The Oak Ridge site was expanded, and two additional sites were built at Paducah, Kentucky and Portsmouth, Ohio. Under the direction of the Department of Energy, the Portsmouth plant was operated by the Goodyear Atomic Corporation and the other two plants by Union Carbide Corporation-Nuclear Division.

As the Department of Energy stated in a June 1985 report, "Until 1974, the United States held a virtual monopoly in the world enrichment market." At that point, the DOE stopped taking new orders because of "projected capacity limitations," and new foreign suppliers of nuclear fuel began signing contracts with utilities abroad. Within 10 years, the U.S. share of the foreign market had dropped by two-thirds. By 1981, the United States, which had been the lowest-priced supplier, was now the highest-priced supplier, a fact that the 1985 DOE report attributes to "the strengthening U.S. dollar." Even U.S. utilities were beginning to turn to the less costly foreign suppliers for nuclear fuel. The dollar figure involved is not insignificant; in 1981, DOE sales of enriched uranium totaled more than $1.4 billion.

Picking up the U.S. market was Eurodif (a consortium of France, Italy, and Spain), Urenco (a consortium of the Netherlands, West Germany, and England), and Techsnabexport (Soviet Union). The foreign suppliers offered lower prices and more favorable contract terms. In addition, because of cutbacks in nuclear power production, a secondary market emerged based on utilities selling off their large inventories of enriched fuel at discount prices—an excess estimated at two to three years of world demand.

The situation came to a head in June 1984, when the DOE announced that it was "embarking on a major initiative to restore the competitive position of the United States in the world enrichment market." Among other things, the DOE set up a Process Evaluation Board to review the advanced uranium enrichment technologies and evaluate which one was most suited to revamp the uranium enrichment industry and make it more "competitive." Two advanced technologies—advanced centrifuge and atomic vapor laser isotope separation—had been funded by the Department of Energy for several years and were in what the DOE described as "the latter stages of development." By June 1985, after 500 reports and 100 man-years of effort, the DOE selected the Atomic Vapor Laser Isotope Separation system, AVLIS, developed by Lawrence Livermore (see box). Unlike other DOE programs, AVLIS will be funded not from tax dollars, but from the sales revenue collected by DOE for enriched uranium.

The DOE Process Evaluation Board found that the AVLIS technology was "less capital intensive, requires significantly less investment prior to start of plant construction, has a lower estimated SWU [separative work unit, explained below] cost, has greater potential for cost reductions through technology improvement, and is more adaptable to deployment in small increments as needed to meet the future needs of the enrichment enterprise." The Board also determined that the AVLIS technology could be supported within the expected projected revenues of the uranium enrichment process, while the advanced centrifuge would need additional financing to support the program.

The AVLIS revolution

As one of the first commercial enterprises based on advanced laser technologies, AVLIS not only could make the U.S. uranium enrichment program "competitive" again, but could be a shot in the arm for the ailing nuclear industry. Pushing forward with the most advanced technologies like laser isotope separation reestablishes the key principle of the American System economics that built this country—cultural optimism. It provides a chance to complete the long-delayed plans for America's second generation of nuclear technology: the fast breeder, fuel reprocessing, the high temperature reactor, the fission/fusion hybrid, and beyond. Without such a revival of nuclear technology—as the Atoms for Peace planners knew—there is no way to supply the energy required to reindustrialize the advanced sector and develop the rest of the world.

As can be seen in Tables 1 and 2, AVLIS will vastly upgrade and cheapen the existing technology: AVLIS uses only one-tenth the power of the gaseous diffusion system, for example, and requires relatively little equipment to achieve enrichment. Lawrence Livermore Laboratory estimates that AVLIS will significantly cut the cost of enriched uranium from $135 per SWU to below $40 per SWU. For each kilogram of unenriched uranium fed into the AVLIS system, one-sixth kilogram of enriched product is produced with just one pass through the system. In contrast, the gaseous diffusion process requires 1,200 passes through the system to convert each kilogram of unenriched product into the same amount of enriched uranium. The AVLIS system is so efficient, in fact, that it could use the depleted uranium that has been processed through the gaseous diffusion system as feedstock.

Taking advantage of the precision of advanced lasers, the

AVLIS system can "tune" to the electron energy levels of uranium-235 with laser light, energize it, and then use an electronmagnetic field to divert the now positively charged uranium-235 atom. This precision gives AVLIS a selectivity greater than 10,000; that is, for each 10,000 ions of the desired isotope, only 1 ion of the undesired isotope is generated. AVLIS has a selectivity advantage over the gaseous diffusion system (and the gas centrifuge) greater than 1 million, because these systems depend on *mass* differences in the isotopes of uranium, which are only about 0.01.

The new AVLIS demonstration facility, which is a joint effort of the lab and Martin Marietta, began enriching uranium in April 1985 using the just completed laser system and an older separator, Mars. The demonstration facility should be operating at full production conditions with the new, full-size separator in 1987-88. The construction of AVLIS has already set records. Working around-the-clock for the past several months, the 400 employees in the laser isotope separation program at Lawrence Livermore, along with an additional 400 contract workers and technicians, completed the new $60 million laser system as well as a $24.5 million new separator demonstration facility one to two years earlier than scheduled.

Lawrence Livermore is also experimenting with the spearation of other isotopes and is seeking private-sector participation in the AVLIS development. Specifically, the lab notes the enrichment of mercury to increase the mass fraction of mercury-196 and thus improve the efficiency of fluorescent lamps, and improving power reactor efficiency with specific isotopes of gadolinium. In addition, the laser system developed for AVLIS may be used in photochemical processing and photocatalytic processes, and may be economical in eliminating catalytic poisons like hydrogen sulfide, which are by-products of crude oil refinement.

The gaseous diffusion method

The gaseous diffusion method of isotope separation has been in use since the Manhattan Project, producing most of the world's enriched uranium. Also known as barrier diffusion, the method is based on the small difference in the mass of isotopic molecules. Uranium hexafluoride gas is pumped through thousands of miles of porous material that acts as a sieve, since the lighter uranium hexafluoride containing U-235 flows slightly faster through the walls of the barrier material. When extracted from the barrier material, the gas then has an increased content of U-235. This gas, now enriched in U-235, is then fed into the next barrier sieve to obtain still higher concentrations of U-235. The efficiency of the process depends on the barrier material and its ability to maintain a stable-size hole for the gas to pass through.

Since the molecular speeds of the two types of uranium molecules differ by only about 0.4%, the enrichment achieved in a single diffusion operation is very small. To enrich the uranium to reactor-fuel level requires repeating this 1,200 times. More than 640,000 kilograms of uranium gas must be circulated to produce a single SWU. Almost all the power consumed in the diffusion process is used to circulate and compress the uranium gas.

Over the past 40 years, the gaseous diffusion program has increased its productivity by making small improvements in the process equipment, thus providing an additional capacity of 5.5 million SWU per year with no increase in power use.

Slowing down progress

The promise of the AVLIS system has been known since the late 1960s. Why, then, did it take so long for the DOE to give the go-ahead for commercial development, and what caused the U.S. uranium enrichment program to founder? The turnaround of U.S. predominance in the uranium enrichment field is directly related to the overall decline in the U.S. nuclear industry and the technological pessimism that swept the nation in the early 1970s and became institutionalized by the Carter administration. When in 1976, the Carter administration intervened to withhold the necessary government permit from Exxon to go ahead with construction of a pilot plant for laser separation, President Carter was quoted as saying, "As long as I am in the White House, laser isotope separation plants will never be built in the United States."

By the early 1970s, the spirit of Atoms for Peace had been replaced with its opposite: the familiar environmentalist litany that small is beautiful, resources are limited, industry is bad for health, Americans are too wasteful, and—that Amory Lovins sleight-of-mind—that one should "create" energy by conservation.

The result was catastrophic for the U.S. nuclear industry and the power supply: The United States gave up its leadership in the civilian nuclear market by refusing to build nuclear plants in developing nations; since 1978, no new nuclear plants have been ordered in the United States, and 24 plants have been canceled or indefinitely mothballed since 1982 alone. The lack of power-generating capacity is the biggest obstacle to the introduction of advanced technologies like lasers to U.S. industry.

One observer, cited in a recent congressional review on radioactive waste policy, describes the problem from the other side—as seen by the cultural pessimists:

> An illusion of certainty was created where, in reality, none existed. Over the years, the sense of tech-

TABLE 1

Isotope separation methods: key costs and economic factors

	Oak Ridge Gaseous Diffusion Plant (Full Power)	New Gaseous Diffusion Plant (Current Tech.)	Current Planned Gaseous Centrifuge Enrichment Plant (GCEP)			1990s Advanced Gaseous Centrifuge System	Advanced Isotype Separation		
			Bldg. 1-2	Bldg. 3-8	Full GCEP 1-8				
			Set III	Set IV	Set IV	Set VI	AVLIS	Molecular Laser	Plasma Proces
Reference Site (in millions of annual rate of SWU capacity		9.3	2.2	9.9	13.2	8.8	8.61	8.75	9.35
Power KWH/SWU	2,360	2,475	135	95	48	65	71	221	
Investment									
Unit Cap: $/annual rate SWU	—	505	1,425	281	498	280	77	107	100
Power Plant: $/annual rate SWU	—	434	24	17	17	8	12	13	39
Total: $/annual rate SWU		939	1,449	298	515	288	89	120	139
Annual Cost									
Power Cost: $/SWU[1]	83	87	5	3	3	2	2	3	8
Oper. Cost: $/SWU	5	9	16	14	14	10	6	8	7
Cap. Cost: $/SWU[2]	—	82	232	46	81	46	13	17	16
Total: $/SWU	88	178	253	63	98	58	21	28	31

1. At 35 mills/KW hr.
2. At 10 years and 10%, 16.28% per annum on total investment. Since the various projects require different building space, auxillaries, etc., an attempt was made to pick reasonably comparable construction periods.

Compared here are the output, investment costs, and annual costs of current and projected methods of isotopes separation, as published by the Department of Energy in "Report of the Energy Research Advisory Study Group on Advanced Isotope Separation," dated November 1980. The measurements are all in mid-1980 constant dollars (no escalation), and all the methods are evaluated on a comparable basis. The basic unit of measurement is the SWU or separative work unit in kilograms.

Under the Gaseous Centrifuge Enrichment Plant are three stages of plant development. An advanced gaseous centrifuge is also shown. Under the Ad
more AVLIS system: the molecular laser and the plasma separation process, both of which were dropped from the DOE development schedule in the early 1980s. Both systems are promising technologies, however, and the TRW's Plasma Separation Process is now experimenting with the production of isotopes to make a "beta decay" battery for use in deep space satellites.

Bear in mind that much of the detail of this technology, production figures, and economics is still classified.

TABLE 2
Comparative costs of uranium enrichment alternatives

Process	Capital	Energy	Labor and material
Gaseous diffusion	High ($300–400 per SWU/year)	High (~2,400 kWh/SWU)	Low
Gas centrifuge (Set V)	High ($400–500 per SWU/year)	Low (~100 kWh/SWU)	Low
Laser isotope separation	Low ($100–150 per SWU/year)	Low (~100 kWh/SWU)	Low

Source: Lawrence Livermore National Laboratory, "Business Development Opportunities in Laser Applications: Isotope Separation," p. 4.

The basic advantages—low capital costs and low energy costs—of the AVLIS system are shown here. As can be seen, the gas centrifuge system is more energy-efficient than gaseous diffusion, but the capital cost is about the same.

The isotope market

The existence of isotopes has been known since the early 1900s, but it was only after the Manhattan Project work during World War II that artificially produced isotopes came into commercial use because they could be cheaply produced in nuclear reactors or by accelerators. The isotopes of an element are basically the same chemically but differ in the number of neutrons present in the nucleus of the atom. Uranium-238 is so designated because it has 92 protons and 146 neutrons in its nucleus, which add up to 238. Uranium-235 has the same number of protons but only 143 neutrons. The similarity of the chemical properties of isotopes is what makes it so difficult to alter the naturally occurring proportions of isotopes.

The Atoms for Peace program spurred the growth of hundreds of applications for isotope research worldwide. In the late 1950s, the International Atomic Energy Agency awarded millions of dollars in research funds to laboratories and institutes, especially in the developing countries, to encourage research on using isotopes in biology, medicine, water resources, agriculture, plant breeding, insect and pest control, livestock production, pollution, and food preservation.

How radioactive isotopes came to be used as biological tracers is quite an unappetizing story. In 1911, George de Hevesy, a pioneer in work with radioactive elements who won the Nobel Prize in 1943, reportedly suspected his boarding-house landlady in Manchester, England, of serving recycled food scraps. One day he took a trace of radioactive material from his laboratory and put it in the leftovers on his plate. Sure enough, several days later when he was served the same dish, he tested it with a gold leaf electroscope and discovered that he was right: The food was radioactive, proving that the landlady recycled table scraps.

Today radioisotopes are an essential part of medical diagnosis and treatment, and new applications continuously being developed. Radiochemicals is a $65 million-a-year business; and radiopharmaceuticals a $200 million-a-year business and growing at a yearly rate of 15%.*

Almost every industry today makes use of isotopes, particularly radioisotopes, in some form—as a tracer, as an instrument gauge, or as a chemical catalyst. Radioisotope instruments can make measurements down to a thousandth of an inch without coming into direct contact with the material or substance being measured, need little maintenance, and are economical. For example, a radioisotope gauge in a galvanizing machine can save 10% of the tin used. Thus the cost of the gauge, approximately $200,000 in the late 1970s, could be recovered within a year.

Similar savings can be realized in other production processes. Gamma radiography, using a source like iridium-192, is used to check the structural integrity of pipes and metal castings without damaging them. Radioisotopes are also used routinely in the making of plastics to graft them to other materials and in geophysical exploration for uranium, oil, and other minerals. Nonradioactive isotopes are used in weapons diagnostics to measure radiation flux density and energy distribution from weapons tests.

* "PSP: The Plasma Separation Process for Isotope Separation," by Steve L. Korn, Laurence N. Harnett, Thomas E. Romesser, and Sol R. Rocklin, *TRW Electronics & Defense/Quest*, Winter 1982-1983, p. 21.

TABLE 3
Current producers of enriched uranium and estimated production data

Producer	Location	Share-holders	Process	Estimated capacity in 1985 (millions of SWU/year)	Estimated price/SWU (1986 $)	Capital cost per SWU/year of capacity (1986 $)	Energy cost (1986 $/SWU)
DOE	Oak Ridge, Tn; Portsmouth, Oh; Paducah, Ky.	USA	Gaseous diffusion	27.3	125–135	300–400	40–80
Eurodif	Tricastin, France	France Italy Belgium Spain Iran	Gaseous diffusion	10.8	90–100	300–400	70–80
Urenco	Capenhurst, England; Almelo, Netherlands; Gronau, W. Germany.	W. Germany U.K. Netherlands	Small gas centrifuges	2	115–130	400–500	3–5
Techsnab	Siberia	USSR	Gaseous diffusion	2.5[1]	100–125	Unknown	Unknown

1. Capacity available to free-world market.

Source: Lawrence Livermore National Laboratory, "Business Development Opportunities in Laser Applications: Isotope Separation," p. 8.

Except for Urenco, the isotope separation systems used worldwide are based on gaseous diffusion. Urenco uses small gas centrifuges, which have a very small energy cost. Foreign suppliers undercut the DOE not only in price but by providing more flexible contracts.

nological optimism embedded itself in the attitudes and thoughts of important agency policymakers. It became, in a sense, an official doctrine at AEC [Atomic Energy Commission]. There is no evidence that its validity was ever seriously questioned until the mid-1970s. This optimism facilitated fragmentation by lulling policymakers; agency personnel never fully recognized that they might create in a sequential, incremental fashion an elaborate technological structure (civilian nuclear power), only to find that the last pieces could not be made to fit.[4]

U.S. enrichment capacity—some economics

The basic unit of measurement in isotope separation is the SWU or separative work unit, which measures the effort required to enrich a mixture of isotopes of a chemical element with one of the isotopes. The enriched uranium fuel produced by 1 SWU will produce about 70,000 kilowatt hours of electrical power.

Starting with natural uranium, which has a 0.7% content of fissionable U-235 and a 99.3% content of U-238, it requires 275 SWUs to obtain 1 kilogram of uranium that has a 98% content of U-235. For fission reactors, which require 3%-5% of U-235, it takes about 4.12 SWUs to produce a kilogram of enriched uranium. A conventional nuclear power plant of 1,000 megawatts uses approximately 27 metric tons of enriched fuel per year. To look at this figure in SWUs, in 1982, the operation of the 78 U.S. nuclear plants required about 7.08 million SWU. The total capacity for civilian production then (and today) using the gaseous diffusion facilities in Oak Ridge, Tenn., Paducah, Ky., and Portsmouth, Ohio was 27.3 million SWU per year.

At present, the DOE price per SWU is $135, compared with $110 per SWU offered by the foreign competitors. (Table 3 compares the capacity and price of DOE enrichment to other current producers.)In the 1970s, the Department of Energy planned to expand enrichment capacity on the basis of an expected demand of 120 million SWU per year in 2000. The ins and outs of what happened to these plans is a sad commentary on the United States as a post-industrial nation, especially in comparison to the Manhattan Project determination to get the job done. The initial plan in 1976 was to

TABLE 4

Characteristics of three sizes of AVLIS enrichment plants.

	3 M SWU/y plant	6 M SWU/y plant	12 M SWU/y plant
Annual production (MSWU/y)	3	6	12
Capital cost (1986 $M)	545	840	1405
Annual operating cost (1986 $M)	71	113	189
Internal rate of return (%)	17.3	20.4	22.4
Payback period (years)	5	4	4
Net present value @ 15% discount rate ($M)	74	306	784
(NPV @ 15%) ÷ (Maximum net investment)	0.14	0.39	0.59

Source: Lawrence Livermore National Laboratory, "Business Development Opportunities in Laser Applications: Isotope Separation," p.16.

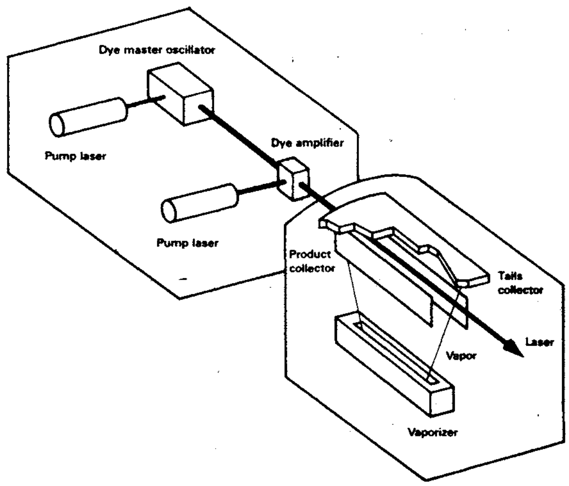
Lawrence Livermore's projections for output and costs of 3-, 6-, and 12-million SWU AVLIS plants. These would be built on the model of the plant now in its demonstration phase at the lab. There is a 22.6% return on capital investment for the largest plant. The figures given are for a generalized project, without consideration of the specific type of ownership of financing for the project.

build a Gas Centrifuge Enrichment Plant in Portsmouth, Ohio designed with a capacity of 8.8 million SWUs per year. This was a more efficient separation system with cost advantages over the gaseous diffusion method because it was less electric-power-intensive, using only 4% as much electrical energy. In addition to this initial plant, another 9-million-SWU facility was expected to come on line every 18 months between 1990 and 2000, in order to keep up with the demand. In the late 1970s and early 1980s, the DOE's projection of world enrichment needs supplied by the United States dropped to *20%* of the level projected in 1976. The DOE attributes the drop to "reduced demand, the strong U.S. dollar, and the emergence of aggressive foreign suppliers." Equally significant, the DOE says, "the cost of gaseous diffusion enrichment grew rapidly with escalating power costs, thereby providing further opportunities for competitors to make serious inroads into DOE's market share." The result was that the gaseous diffusion plants are operating at about one-third of their combined capacity.

As the projected demand waned, so did the DOE's plans to increase enrichment capacity. The June 1985 DOE report puts it this way: "The new Gas Centrifuge Enrichment Plant mission became to replace rather than augment GDP [gaseous diffusion] capacity with the more economical centrifuge technology." In other words, the capacity would remain the same; only the technology would change. Then, in the early 1980s, when electricity prices stabilized, the DOE reports that the centrifuge machines no longer appeared "cost competitive," and therefore work on this project was "slowed," while work was accelerated on an advanced gas centrifuge.

By October 1985, a total of $2.6 billion will have been

Atomic Vapor Laser Isotope Separation (AVLIS)



In contrast to the gaseous diffusion and the gas centrifuge methods of isotope separation, which are based on the tiny mass differences between U-238 and U-235, the Atomic Vapor Laser Isotope Separation exploits an entirely different property of the uranium isotopes: electron energies. U-238 and U-235 have different electron energies, so they absorb different wavelengths of light. AVLIS achieves the enrichment by selectively tuning in to the U-235 wavelength.

The AVLIS process has two major components—a laser system and a separator system. Metallic uranium is melted and vaporized using an electron beam. Dye lasers then produce beams of red-orange light precisely tuned in order to activate the U-235 atoms—giving them a positive charge. These U-235 ions are then extracted electromagnetically, condensing on a product collector. The dye lasers are pumped by copper vapor lasers.

The atoms of U-238 receive no charge and pass through the collector stage. The separated isotopes are then cast and stored in metallic form.

In contrast to the gaseous diffusion and centrifuge system, AVLIS requires only one pass through the process to achieve the required uranium enrichment.

invested in the Gas Centrifuge Enrichment Plant in Portsmouth, construction is 98% complete, and $40 million in capital would be required to complete the machine installation and startup. Now, however, all work on the centrifuge project has ceased, and this technology was passed over for the more advanced AVLIS system. The DOE Process Evaluation Board noted in making this decision that the reason for the total shutdown, as opposed to a partial operation or a standby status, is that, according to their "business strategy" for the government's enrichment program, there is excess gas diffusion capacity and, because of lower electricity prices, there is a "low marginal cost" of increasing the gas diffusion production if necessary.

'Business' strategy vs. progress

In other words, the DOE's "business" strategy is to abandon the 98-percent-complete, more advanced system because in the DOE's cost/benefit framework of analysis the project would at best "break even" with gearing up the existing, under-utilized gaseous diffusion program to meet any increased need for enriched uranium. The DOE report also stated that the department would work with Congress to explore "alternative, non-enrichment uses" of the existing facilities.

Unfortunately missing from the DOE's business strategy is the concept of how the introduction of advanced technologies into the economy is the driver that moves the entire economy forward at an increasing rate. Although 100 man-years were spent in evaluating AVLIS versus the advanced centrifuge program, the simple economics of the Apollo program—which, conservatively estimated, returned $14 to the economy for every $1 expended—are not considered in the discussion. How many technology spinoffs from AVLIS, or from the TRW Plasma Separation Process, dropped from DOE consideration in the early 1980s, could now be increasing the production of U.S. industry?

Along the same lines, the DOE's evaluations accept without question that the "market" has somehow gutted the U.S. nuclear industry, that this is just a fact of life. Yet by renewing the spirit that informed the Atoms for Peace program, the United States could be resuscitating its dying industry and industrializing the rest of the world by building 3,000 gigawatts of nuclear capacity by the year 2000. The resulting demand for enriched uranium would require a gear-up of the current gaseous diffusion, putting on line the gas centrifuge, and moving full speed ahead with the more advanced separation technologies.

Notes

1."PSP: The Plasma Separation Process for Isotope Separation," by Steve L. Korn, Laurence N. Harnett, Thomas E. Romesser, and Sol R. Rocklin, *TRW Electronics & Defense/Quest,* p. 21.

2.*Ibid.*, p. 22.

3.Daniel Metlay, consultant for the Office of Technology Assessment, as cited in "Managing the Nation's High Level Commerical Waste," Office of Technology Assessment (Washington, D.C.: U.S. Congress), March 1985, p. 84.

The gas centrifuge method

The use of centrifuges to separate isotopes was proposed as early as 1919 in the laboratory of J.J. Thomson. However, an operating centrifuge was not successfully demonstrated until 1934, by Jesse W. Beams of the University of Virginia. Centrifuges were developed during the Manhattan Project and operated successfully, but the materials were not strong enough to upgrade the device for commercial use. Beams continued to research the method and in 1960 received $6 million from the Atomic Energy Commission to develop the technology.

In the 1970s, six private firms invested $100 million each in building centrifuge demonstration facilities and associated research that contributed to the plan for a Gas Centrifuge Enrichment Plant, which was 98% completed but has now been abandoned by the DOE.

In each centrifuge (a rotor inside an evacuated casing), the uranium hexafluoride is spun at high speeds. The heavier isotope, U-238, tends to collect near the outer walls of the centrifuge where it can be drawn off. The separative effect is increased by an axial countercurrent flow of gas within the centrifuge. The stream of gas enriched with the lighter U-235 then flows to the next stage of higher enrichment, while the stream depleted in U-235 flows to a stage with lower enrichment.

Since each centrifuge can process only a small amount of uranium hexafluoride, a number of units must be connected in a series called a cascade to obtain the desired enrichment. A centrifuge plant requires only about 4% of the power needed for a gaseous diffusion plant—100 megawatts for a plant of 8.8 million SWU capacity. There are also additional savings from the lower amount of water needed for cooling.