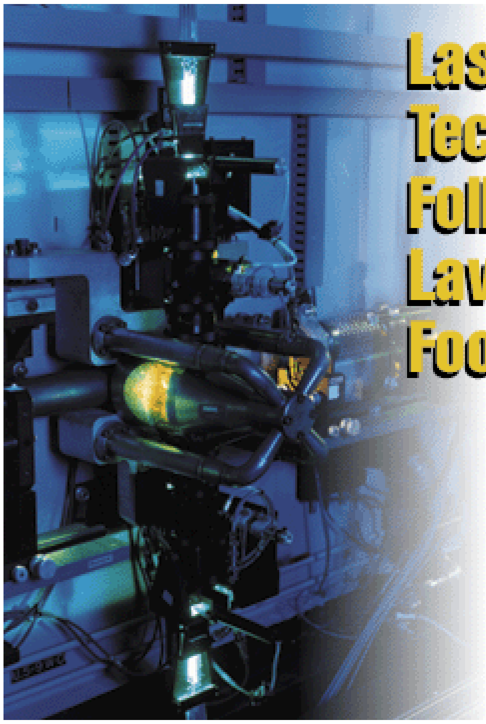


Laser Technology Follows in Lawrence's Footsteps

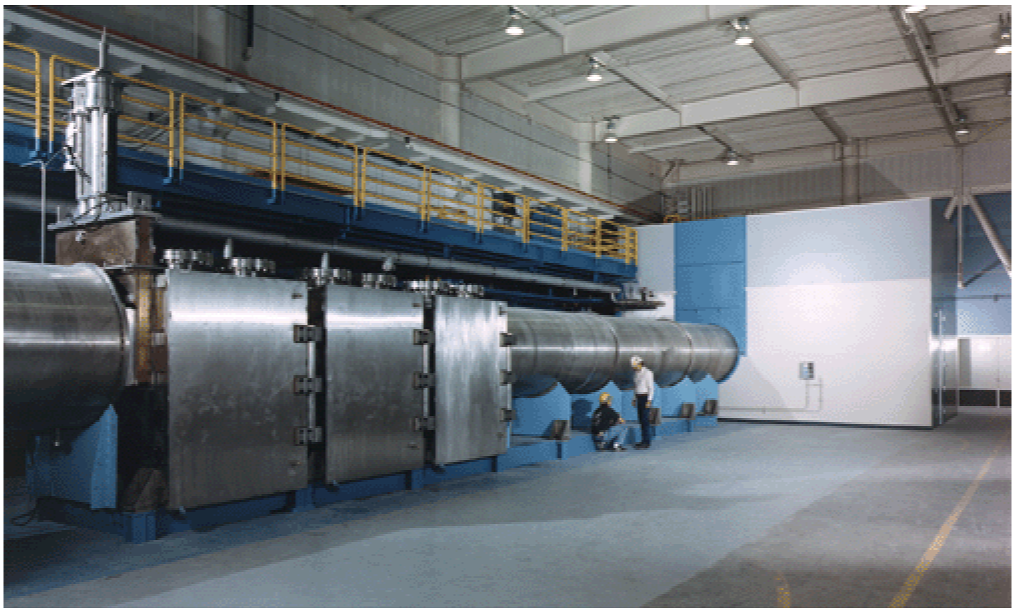
Precisely tuned lasers light the way to advances in energy, medicine, and astronomy.

ONE of the toughest scientific challenges has been to effectively—and inexpensively—separate a desired isotope of a chemical element from the remaining isotopes for uses ranging from medicine to energy to weapons applications. Traditionally, isotope separation has been performed through the techniques of gaseous diffusion and gas centrifuge. Over the past two decades, scientists and engineers at Lawrence Livermore have developed another technique, fundamentally different and much more efficient, called laser isotope separation (LIS). The technique is based on the fact that different isotopes of the same element, while chemically identical, absorb different colors of laser light. Therefore, a laser can be precisely tuned to ionize only atoms of the desired isotope, which are then drawn to electrically charged collector plates.

LIS was originally developed in the 1970s as a cost-effective, environmentally friendly technology to supply enriched uranium for nuclear power plants and special nuclear materials for national security needs. Over the years, funding of about $2 billion was invested to develop the technology at Lawrence Livermore and to successfully demonstrate it with an integrated, full-scale pilot plant. This step was achieved in the early 1990s for special nuclear materials separation and in the late 1990s for commercial uranium enrichment applications.

The uranium enrichment process was being tested successfully at Livermore's pilot plant when the United

States Enrichment Corporation (USEC) suspended funding for the project in mid-1999. LIS technology, however, is currently finding other important applications in energy, medicine, astronomy, and industry. Livermore scientists are also proposing its use for tapping the energy value remaining in the tailings left from decades of government uranium enrichment activities.



The separator demonstration facility at Lawrence Livermore's laser isotope separation (LIS) pilot plant tested full-scale equipment. One of three separator units shown for enriching uranium was operational for demonstrations. Also visible are beam tubes for transporting precisely tuned laser light to the separator units.

Lawrence Led the Way

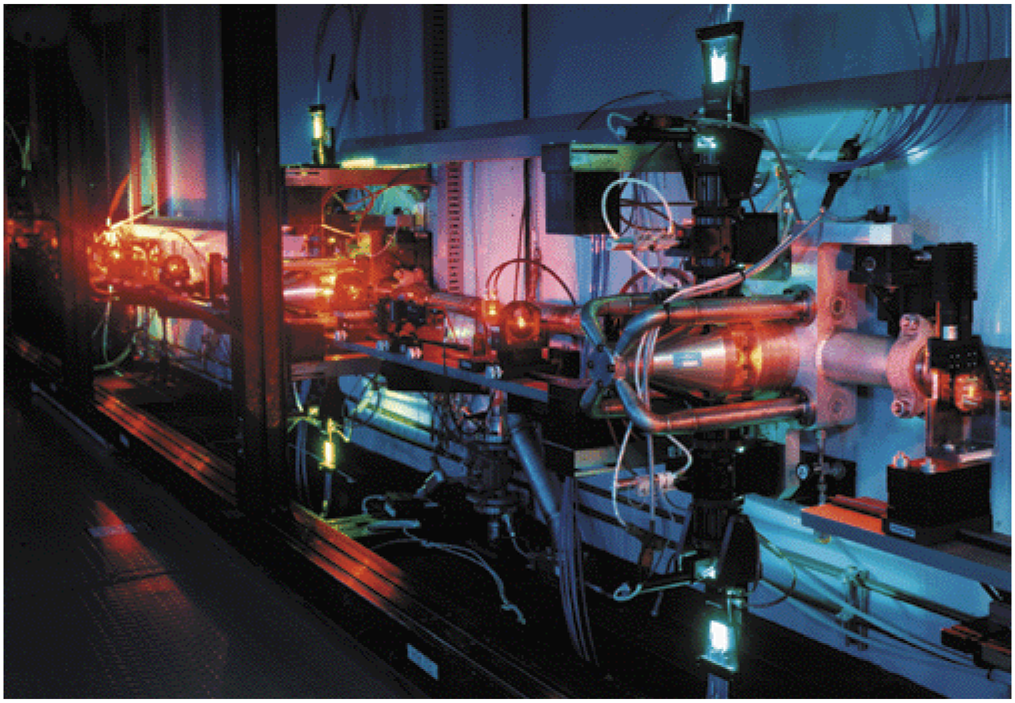
It seems appropriate that a national laboratory named for Ernest O. Lawrence should have developed a technologically superior solution for enriching uranium. During World War II, Lawrence led the effort to enrich the uranium used in the Manhattan Project to build the world's first nuclear weapon. He pioneered an electromagnetic enrichment technique based on research at his cyclotron facility. This Calutron separation technology, named after the University of California, was transferred to production facilities at Oak Ridge, Tennessee, where it separated uranium isotopes in a slow and expensive process.

In the early 1970s, as part of the Laboratory's growing effort in laser technology research, Livermore scientists began experiments using lasers to enrich uranium. By the end of the decade, scientists were reporting important progress, and the project was attracting talented physicists and engineers from around the nation.

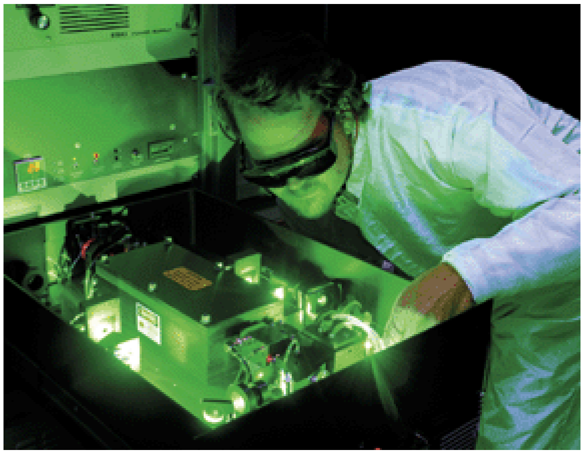
Development of process science, technology, and hardware was so impressive that in 1985, the Department of Energy selected LIS (also called Atomic Vapor Laser Isotope Separation, or AVLIS) as having the best potential to provide a low-cost, environmentally sound method to enrich uranium for the U.S. and its international trading partners. DOE's goal was to replace, in an orderly way, the aging and energy-inefficient gaseous diffusion plants in Ohio and Kentucky.

Plant-scale laser and separator hardware began operation in 1986, while researchers were continually improving their performance and reliability. The early 1990s marked the first tests with full-sized components in integrated systems producing enriched uranium over many tens of hours. The Energy Policy Act of 1992 transferred the U.S. government's uranium enrichment activities to USEC, which at that time was a government corporation charged with supplying the nuclear fuel industry with enrichment services through gaseous diffusion technology.

In July 1994, after a two-year period during which Livermore's LIS activities were on a standby status, USEC gave the green light for advanced development. The technology was then transferred from DOE to USEC for commercialization, representing the largest technology transfer in the Laboratory's history.



LIS plant-scale dye laser chains absorb green light from solid-state lasers and reemit it at a color that can be tuned to the isotope of interest. For uranium enrichment, the green light was converted to red–orange light of three different wavelengths that are absorbed only by uranium-235.



The introduction of solid-state lasers to energize the dye lasers with green light made a significant contribution to meeting the pilot plant's cost and operating efficiency goals.

Technology Was Proven

A pilot enrichment plant, completed at Livermore in the fall of 1997, became the focal point for the LIS team composed of experts from Livermore, Bechtel National Inc., Duke Engineering, On-Site Engineering, Babcock and Wilcox, Lockheed Martin, AlliedSignal Corp., and USEC. The team moved forward with testing commercial-scale equipment. Important improvements over time included making key separation upgrades for better performance and reliability, introducing deformable optics for laser beam uniformity, and substituting compact diode-pumped solid-state lasers for copper lasers to energize the all-important dye lasers. This latter change significantly reduced costs and space requirements.

The pilot plant operated for more than one-and-a-half years, processing several thousand kilograms of uranium in a series of tests aimed at verifying component performance, operational lifetime, and economics. "Running the pilot facility was not an experiment," notes Livermore physicist Steven Hargrove, a former senior LIS scientist. "This was a 24-hours-a-day demonstration of industrial capability using full-scale hardware." In tandem with the long-term tests, scientists and engineers began the first stages of designing and licensing a commercial plant.

By December 1997, the plant had achieved its target for separator lifetime, which was 400 hours of continuous operation before needing refurbishment. However, the next three tests during 1998 fell well short of 400 hours because of unexpected component corrosion. The LIS team traced the problem to a minor impurity in the uranium, verified this diagnosis in a 290-hour test, and moved the separator effort back on track.

By March 1999, the pilot demonstrations had verified projections that the technology could achieve enrichment at costs comparable to those of current U.S. gaseous diffusion, even without the planned pilot improvements. Project managers were preparing both final engineering improvements and additional 400-hour enrichment tests intended to address two remaining economic factors: separator lifetime and enrichment efficiency. The goal was to conclusively demonstrate within a few months' time the basis for projecting that the LIS plant could enrich uranium at costs equal to or below those of all existing technologies.

Development efforts to achieve high enrichment efficiency centered on improving laser beam uniformity and uranium vapor conditions. Eighty percent of the plant's enrichment efficiency goal was achieved in several tests, including the 290-hour demonstration tests in March 1999 that had laser systems operating at record power levels. Engineering upgrades were in place to address about half the remaining shortfall in forthcoming tests and to fully meet the 100-percent target during final design of the commercial plant.

However, the tests were interrupted by USEC's decision in June 1999 to halt development of LIS technology because a combination of near-term factors limited its funds. These factors included market-driven price declines for enriched uranium, significant cost increases to operate U.S. gaseous diffusion plants, and the need to continue shareholder dividends. USEC also judged expected investment returns were insufficient to outweigh the usual anticipated risk of new technology.

The decision halted the efforts of more than 500 people, including some 300 Livermore employees. In making the announcement, USEC President and Chief Executive Officer William Timbers, Jr., said, "The Lawrence Livermore team has displayed outstanding dedication, creativity, and responsiveness in its efforts to develop and commercialize AVLIS."

Enriched uranium produced at the Livermore pilot plant was collected as nuggets the size and thickness of several quarters. The nuggets were packed in 55-gallon drums for shipment to commercial fuel fabricators.

An operator removes enriched product from the separator withdrawal canister.

LIS Offers Advantages

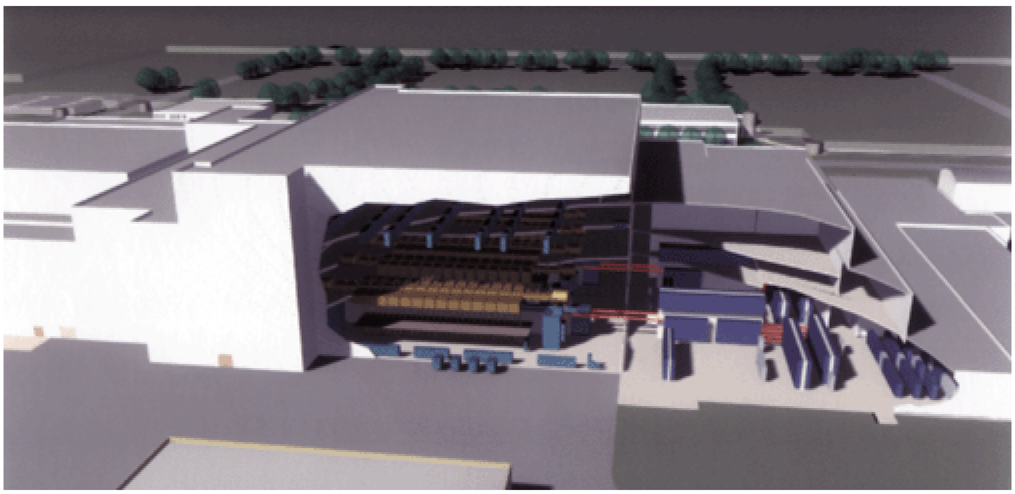
Livermore physicist Bruce Warner, former LIS program leader, notes that USEC's decision was no reflection on the strong advantages and technical capability of LIS. For example, the LIS process uses only 5 percent of the electricity consumed by existing gaseous diffusion plants, and LIS facilities would cost substantially less to build than those for other enrichment techniques such as centrifuge technology.

The enrichment of uranium, from natural levels of 0.7 percent uranium-235 (^{235}U) to between 3 and 5 percent ^{235}U, is achieved in a few passes with LIS, a great improvement over the hundreds to thousands of passes required by other processes. This translates into a much smaller plant and production costs substantially below those of either gaseous diffusion or gas centrifuge technology. "With LIS, it doesn't take much real estate to make a lot of product," says Warner.

Indeed, the system is remarkably compact. A vacuum chamber holding one separator unit produces output equivalent to that of several thousand of the best commercial centrifuges. A commercial LIS plant would use 84 enrichment units, compared to more than 150,000 centrifuge machines.

Hargrove notes that LIS also offers strong environmental, safety, and health advantages. Instead of using uranium hexafluoride, the starting material required by other processes, LIS uses uranium metal, which is less hazardous. Compared to centrifuge or gaseous diffusion, the laser process requires about 30 percent less natural uranium ore to produce a comparable amount of enriched product, which also minimizes the amount of uranium tailings by about 30 percent.

"LIS technology is the future of uranium enrichment, whether or not the U.S. commercializes it," says Warner. He notes that France and Japan also have LIS development programs and that the nation first deploying the technology for uranium enrichment will enjoy important economic advantages in the world marketplace. "We want to be sure our nation has a reliable and commercially attractive production source of enriched uranium in the 21st century, preferably one based on the best U.S. technology," says Warner.



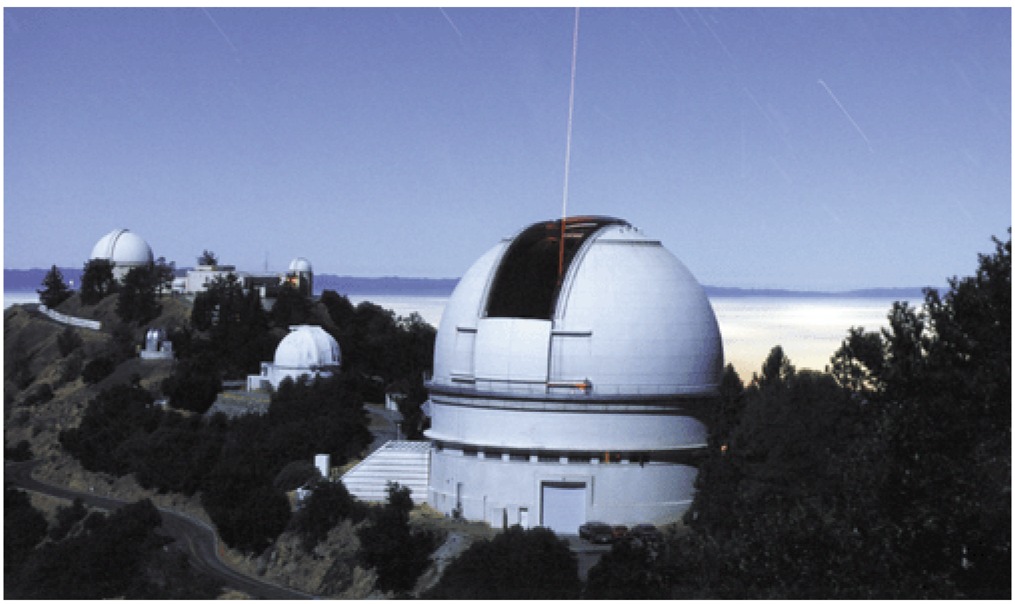
An engineering drawing of a commercial uranium enrichment plant using LIS technology. The cutaway shows banks of separators on the left, lasers on the right, and beam tubes (red) connecting the two systems.

Spinning Off a Star

A natural outgrowth of Livermore's successful LIS development effort was research into other isotopes that could be supplied efficiently using similar technology. More than 60 potential spinoffs were identified by Livermore scientists in a study for the National Academy of Sciences and the National Academy of Engineering. One spinoff, called the laser guide star, has been of immense use to astronomers because it removes the effects of atmospheric turbulence that blurs the images taken by Earth-bound telescopes. The technology has been installed at several leading telescopes worldwide.

The laser guide star uses technology originally developed for the LIS effort. The guide star begins with green light from flashlamp-pumped, solid-state lasers beneath the main floor of the telescope dome. The light travels through fiber-optic lines to a compact dye laser similar to that used in uranium enrichment. The dye laser converts the light from green to yellow, and a beam projector mounted on the telescope directs the yellow light up through the upper atmosphere.

At an altitude of about 95 kilometers, the laser beam hits the layer of sodium atoms that are continuously produced by burning micrometeorites. The light excites the sodium atoms, causing them to emit yellow light in all directions and create a sharply defined guide star. An adaptive optics system at the telescope corrects the guide star image for atmospheric distortions. The corrections made to the guide star's light sharpen the image of all of the celestial objects in the same patch of sky under the telescope's view.



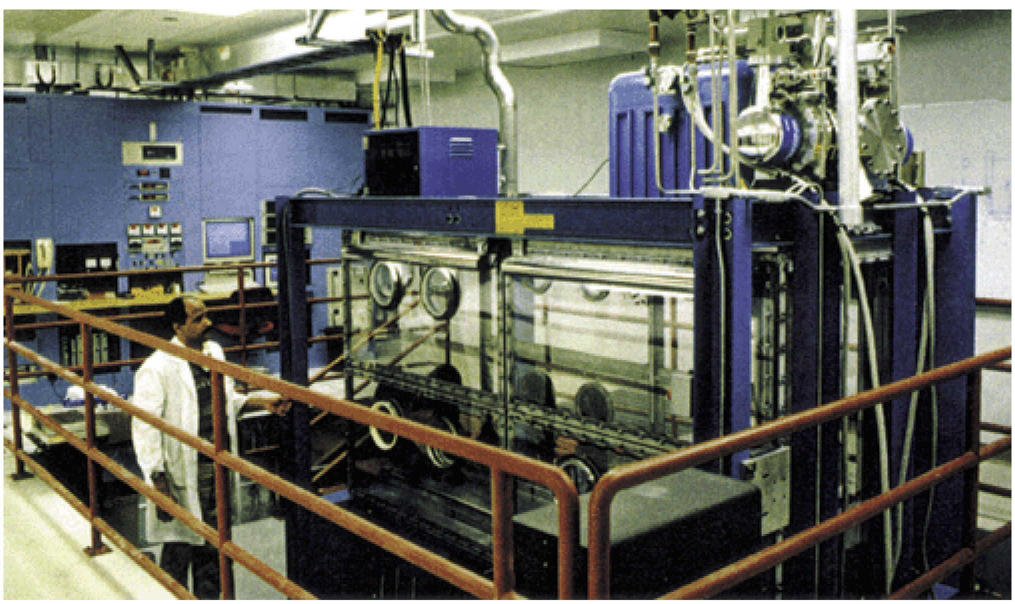
Laser light beamed from California's Lick Observatory hits a layer of sodium atoms at an altitude of about 95 kilometers to create a guide star, which is used to see celestial objects more clearly through a telescope. The guide-star technology was a spinoff from the laser isotope separation effort.

Enrichment for Fuel Efficiency

Another promising spinoff of LIS applications, endorsed by the National Academy of Sciences, is enriching gadolinium for use in boiling-water nuclear power plants. Fuel rods now contain about 8 percent of natural gadolinium, which is a mixture of seven isotopes. The odd-numbered isotopes, gadolinium-155 and gadolinium-157, are of interest because they absorb neutrons to control excess reactivity of burning fuel rods, which translates to more efficient use of the fuel and reduced reactor waste.

LIS technology can be used to double the concentration of odd-numbered gadolinium isotopes, so reactor fuel would need only half its current amount of gadolinium, further contributing to fuel burnup efficiency. Hargrove says that enriched gadolinium could be an important constituent in future nuclear fuel designs because it could permit significant increases in fuel burnup time. Enriched gadolinium could also play an important role in mixed oxide reactor fuels that burn surplus plutonium from nuclear weapons; DOE is considering this concept. An LIS plant for gadolinium would be similar to a uranium enrichment system, but it would require only about one-tenth the hardware to economically meet market-demand projections.

Another product with similar benefits is enriched erbium-167, currently used in its natural form in reactor fuel for pressurized-water nuclear power plants. Test runs at Lawrence Livermore have verified the enrichment process for both gadolinium and erbium and have produced kilograms of each material. Together, they could potentially command a 6,000- to 9,000-kilogram annual world market of about $50 million per year.



A medical laser isotope enrichment facility was built for demonstrating cost-effective separation of isotopes of interest to the medical research and medical treatment communities. The facility's separator is shown above. The dye and solid-state lasers are housed in an adjoining room.

Isotopes for Medical Diagnostics

Livermore scientists have also investigated the technical and economical feasibility of laser isotope separation for medical diagnostic tests and research. In 1998, a research team supervised the completion of a facility constructed for separating the isotopes of a wide range of metals for medical use.

Last year, that team developed the capability to access the 250- to 450-nanometer wavelength range (required for many isotopes of interest) with tunable, high-power, and high-repetition-rate dye lasers. The team also successfully demonstrated a master oscillator that produces more than 10,000 pulses per second. Such pulse rates are critical for missions that require narrowly tuned and high-repetition-rate dye laser light.

Livermore physicist Karl Scheibner says that LIS technology would help revitalize DOE's medical isotope production program, which uses World War II-era Calutron technology. DOE's sales of medical isotopes have fallen significantly as a result of competition from Russia's modernized electromagnetic separation plants and Europe's centrifuge separation facilities. A study conducted last year for DOE found that small machines using electromagnetic, plasma-separation, and LIS technologies could all have an important role in providing medical isotopes at substantially reduced costs.

For example, calcium-43 used in medical research costs about $400 per milligram when produced on Calutrons but would cost just a few dollars per milligram using LIS technology. Scheibner believes that LIS will permit significant new contributions to health care, especially in the area of new diagnostic procedures employing isotopes. Scheibner says that commercial production of enriched isotopes would probably not take place at Lawrence Livermore. Instead, Livermore engineers would transfer the process to industry.

How LIS Works

Laser isotope separation (LIS) is based on the fact that different isotopes of the same element, while chemically identical, have different electronic energies and therefore absorb different colors of laser light. The isotopes of most elements can be separated by a laser-based process if they can be efficiently vaporized as atoms. For those elements to which it can be effectively applied, LIS is likely to be the least expensive enrichment technology.

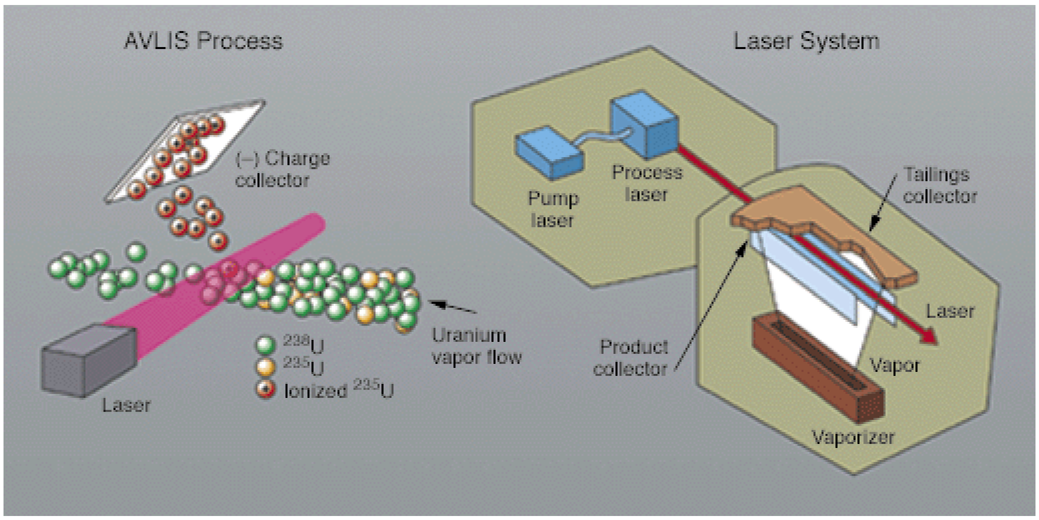
The best-known laser isotope process is for uranium enrichment because the ^{235}U isotope is fissile; that is, it can sustain a nuclear chain reaction to provide energy. Uranium ore is usually processed to increase the natural concentration of ^{235}U from 0.7 percent to about 4 percent to fuel the commercial nuclear power plants that are in widespread use today.

In LIS enrichment, uranium metal is first vaporized in a separator unit contained in a vacuum chamber. The vapor stream is then illuminated with laser light tuned precisely to a color at which ^{235}U absorbs energy.

The generation of laser light starts with diode-pumped, solid-state lasers providing short, high-intensity pulses at high repetition rates. This green light from the solid-state lasers travels via fiber-optic cable to energize high-power dye lasers. The dye laser absorbs green light and reemits it at a color that can be tuned to the isotope of interest. In uranium enrichment, the light converts to three wavelengths of red-orange light, which is absorbed only by ^{235}U.

Each color selectively adds enough energy to ionize or remove an electron from ^{235}U atoms, leaving other isotopes unaffected. "The uranium atoms are subjected to a razor-sharp beam," notes Livermore physicist Steve Hargrove. "Given the several kilowatts of high average power of the dye laser beam, it's a significant achievement that the wavelengths are stable to better than 1 part in 10 million and that the beam's ability to travel long distances is nearly perfectly preserved."

Because the ionized ^{235}U atoms are now "tagged" with a positive charge, they are easily collected on negatively charged surfaces inside the separator unit. The product material is condensed as liquid on these surfaces and then flows to a caster where it solidifies as metal nuggets. The unwanted isotopes, which are unaffected by the laser beam, pass through the product collector, condense on the tailings collector, and are removed.



In the laser system used for the LIS uranium enrichment process (right), electrons from the ^{235}U atoms are separated (left), leaving positively charged ^{235}U ions that can be easily collected for use.

High Value in Tailings

Lawrence Livermore scientists also propose using LIS technology for another DOE mission, one closely related to enrichment of natural uranium. Their idea is to use LIS to recover the energy value remaining in the tailings from several decades of uranium enrichment activities at U.S. gaseous diffusion plants, activities that were undertaken for both commercial and defense purposes. "LIS could clean up as much as 60 percent of DOE's tailings inventory with full cost recovery as well as generate significant profits. It would also provide important environmental, energy conservation, and national security benefits," says Hargrove.

In all, over 700 million kilograms of depleted uranium hexafluoride (DUF_6), containing 475 million kilograms of uranium, have been generated by the U.S. government. The material is stored in nearly 60,000 steel cylinders at Oak Ridge National Laboratory and at the Ohio and Kentucky gaseous diffusion plants. Although DUF_6 does not present a serious radiological threat, it is a potential chemical hazard and is under safe management by DOE's cylinder surveillance and maintenance program. DOE is considering long-term plans to convert DUF_6 into a more environmentally acceptable and nonhazardous form (either an oxide or uranium metal) before final disposition of the tailings.

Lawrence Livermore laser scientists note that an LIS plant could convert the tailings first to metal (required for the LIS enrichment process), enrich the uranium to recover its energy value, and finally convert the leftover tailings to oxide for burial. Livermore projections show that LIS can profitably reenrich about 60 percent of the tailings inventory (the proportion containing more than a quarter of a percent of ^{235}U). By recovering energy from existing tailings, the LIS plant would dispose of over 11 million kilograms of uranium tailings every year and provide enough fuel to power 40 gigawatt-class nuclear power plants (about 8 percent of America's electric power needs).

Hargrove says that revenue from enriched uranium produced by the plant, even at prices well below current market levels, would more than pay for both the plant's construction costs and all operating costs. The market is currently at about $80 to $85 per SWU (separative work unit, the standard measure of enrichment services). Even at $60 per SWU, DOE could recover all of its costs as well as generate a profit of $2.4 billion over the 25-year life of the LIS plant. This profit could be used to more than offset costs to clean up the remaining 40 percent of tailings not economical for LIS.

"There's obviously a lot of value in the tailings that's waiting to be exploited," says Hargrove. As an advanced, low-cost U.S. enrichment technology, LIS could be used to clean up a significant portion of the depleted uranium inventory and do so profitably, he says. But of more importance, the LIS depleted uranium plant would also preserve technology fundamentally important to both national and energy security, technology that would otherwise be lost.

Hargrove emphasizes that LIS is a demonstrated engineering capability. "We're prepared to move ahead and apply it to uranium enrichment applications for the government as well as to a host of scientific, medical, and energy applications."

—Arnie Heller

Key Words: Atomic Vapor Laser Isotope Separation (AVLIS), Calutron, diode lasers, erbium, E. O. Lawrence, gadolinium, gas centrifuge, gaseous diffusion, laser guide star, laser isotope separation (LIS), Manhattan Project, uranium enrichment, United States Enrichment Corporation (USEC).

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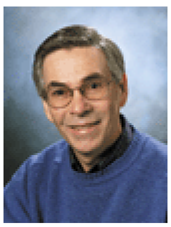
ABOUT THE SCIENTIST



STEVEN HARGROVE received his B.S. and M.S. in physics from the University of California at Los Angeles. He joined the Laboratory in 1975 in the Laser Programs Directorate, where one of his first responsibilities was to identify and develop laser and electrooptic technologies for strategic materials and commercial isotope separation applications. That investigation broadened in scope and responsibility over the years, culminating in his work on the atomic vapor laser isotope separation (LIS) process to enrich uranium to fuel commercial nuclear power plants. Hargrove has been involved in the LIS effort since its beginnings, starting with work on laser systems design and cost and process analysis, to developing isotope separation for naval propulsion, commercial nuclear fuel, and industrial laser materials processing. Hargrove was the senior scientist supporting the director of the uranium enrichment commercialization effort and the program leader.

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