EIR Science & Technology

Industrial laser chemistry required for Mars mission

Among the near-term economic benefits of the push to colonize Mars by the year 2027, is the industrial revolution that must occur on Earth. Robert Gallagher reports.

Evaluation of the economic impact of the Mars colonization mission can begin with a listing of those technologies that the mission requires, and must bring into existence on a large industrial scale, in order to accomplish the goal of the establishment of a permanent Mars colony of hundreds of thousands of persons within the next 40 to 50 years. It is such technologies that will bring about an industrial revolution on Earth.

Among these technologies are:

1) High power tunable lasers such as the free electron laser, that will produce coherent radiation in the infrared, visible, and even shorter-wavelength ultraviolet and x-ray regions of the electromagnetic spectrum. These lasers are required by the Mars mission as igniters for one of the two main types of fusion propelled rockets now being designed: inertial confinement fusion (ICF) spacecraft.

In an ICF rocket, lasers will focus a powerful, short pulse of coherent radiation onto a pellet of fusion fuel, which then detonates, releasing approximately a thousand times more energy than that of the laser pulse used to ignite it. This fusion micro-explosion produces the thrust for the rocket.

These lasers will also serve as the principal tool in the production of fusion rocket fuels, such as deuterium and tritium (the heavy isotopes of hydrogen), and in the fabrication of advanced materials required by the Mars program.

The Mars program will require these lasers as early as 2010 for assembly of the first fusion propulsion systems. As a result, its laser development program will in part drive development of new ballistic missile interceptors for strategic defense.

2) Laser chemistry, the use of coherent radiation to drive chemical processes, such as isotope separation. The Mars colonization's annual needs of tens to hundreds of thousands of tons of fusion fuel, combined with the requirements of terrestrial and lunar fusion power plants, require the establishment of large-scale industrial enterprises occupied with the separation of deuterium and tritium from molecular compounds of hydrogen. These technological advances are only two of the many required by the Mars program, but development of just these two technologies, will force through a revolution in industrial chemical processing.

Isotope separation processes and other applications of laser chemistry, will demonstrate the superiority of what are termed "non-equilibrium" laser and plasma chemistry processes, over conventional thermal equilibrium chemistry. In the "non-equilibrium" chemistry made possible by lasers, ordinary chemical thermodynamics are overridden by directing into a substance coherent radiation tuned to specific wavelengths that act only on that portion of the material where work must be done; the rest of the material remains "cold." In thermal equilibrium chemistry, on the other hand, reactants are heated uniformly; this limits productivity and throughput as is discussed below.

By making tunable high-power lasers widely available, the Mars program will permit the introduction of "non-equilibrium" laser chemistry processes across a broad front in industry; this would not be possible without tunable lasers since the action required to produce specific chemical products requires wavelengths of light specific to each process.

Results to date in experimental laser chemistry are considered surprisingly anomalous by contemporary chemists. This gives us some taste of the revolution ahead.

The National Research Council's Committee to Survey Opportunities in the Chemical Sciences, chaired by George Pimentel, wrote in its 1985 report:

> Absorption of light can change the chemistry of a molecule dramatically. After excitation, familiar atoms can have unexpected ideas about what constitutes a comfortable bond angle; functional groups can have drastically different reactivities; acid dissociation constants can change by 5 to 10 orders of magnitude; ease of oxidation-reduction can be drastically altered; and stable structures can be made reactive. The energy absorbed by the molecule puts its chemistry on a high energy "hypersurface" whose reactive terrain can be nothing like the ground state surface below, the one that chemists know so well.

Regarding one area of laser chemistry, Wayne Danen, a laser chemist at Los Alamos National Laboratory, wrote in the journal *Optical Engineering* in 1980: "The ability of a pulsed infrared laser to override the thermodynamics of a system is unique and cannot be duplicated by any type of catalyst or conventional heating."

It is no wonder that the Pimentel report states in the conclusion to its Executive Summary: "In the next two decades there will be dramatic changes in our basic understanding of chemical change and in our ability to marshal that understanding to accomplish deliberate purpose."

Consideration of the atomic vapor laser isotope separation (AVLIS) process developed for uranium enrichment by Avco Research Laboratory and Lawrence Livermore National Laboratory, will suggest something of the quality of these "dramatic changes." AVLIS is the first laser chemistry process being applied on an industrial scale. Construction of a demonstration plant in Livermore is complete. Since there is an existing, industrial-scale uranium isotope separation process, we have the data available for making a thorough-going comparison between the physical economics of present and future processes. Paradoxically, though still very much classified, there is more detailed information available on laser isotope separation of uranium, for the production of nuclear reactor fuel and for military applications, than most other laser chemistry processes, precisely because of the premium the U.S. government has put on its development.

The problem of uranium enrichment

The fission of uranium-235 (that isotope or "variety" of uranium with 235 neutrons and protons) is presently the basis of commercial nuclear power. Unfortunately, it is a rare isotope and occurs with a concentration of only 0.71% in natural uranium, the remainder of which is the more abundant but non-fissile U-238 isotope. The concentration of U-235 must be increased (or enriched) to about 3.2% to produce uranium that will sustain a chain reaction in a power plant. This requires increasing the concentration by a factor of 4.5,

a problem that at first glance, may not appear to be so difficult, until one realizes that these two isotopes whose nuclear characteristics are so different, are almost indistinguishable from the standpoint of conventional chemistry. For example, they differ in mass by only 1%.

Several techniques were discussed and developed for the enrichment of uranium before the action of lasers was considered, but the one that the Atomic Energy Commission settled on in the 1940s was a process of pumping heated uranium hexafluoride gas through diffusion barriers in a series of large separation stages (4 meters in diameter); the process is named "gaseous diffusion" (see **Figure 1**). It is based on the fact that the desired U-235 isotope travels slightly faster through the separation units because it is 3 neutrons lighter. Since the system acts upon the uranium gas as a homogeneous mixture in thermal equilibrium with itself, and does not selectively pump energy into either isotopic species, gaseous diffusion is an example of an equilibrium thermal chemical process.

The theory of gas dynamics predicts that a single stage of gaseous diffusion can enrich uranium in U-235 by only 0.43%. In actual plant operation, the enrichment factor is less than half that value. A simple calculation shows that with such a low single-stage enrichment factor, 1,200 separate stages are required to enrich natural uranium to reactor-grade fuel. From startup, it is necessary to circulate 640 metric tons of uranium hexafluoride through the entire system before 1/6 of a kilogram (0.4 pounds) of enriched uranium is produced.

The gaseous diffusion process employs 2,000-3,000 horsepower electric motors on each separation unit applying a power density of 120-180 kilowatts per meter squared of

FIGURE 1
Schematic of single gaseous diffusion stage
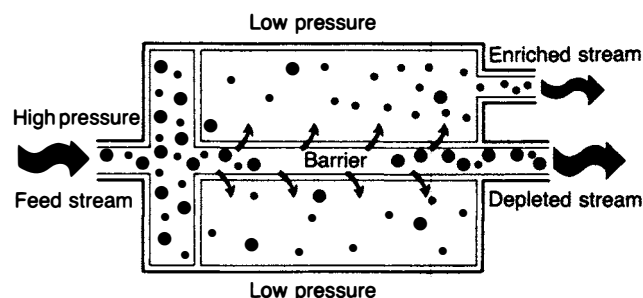
The schematic shows how the high pressure feed stream of heated uranium hexafluoride (UF₆) gas is diffused through pores in a cylindrical barrier. More of the lighter ²³⁵U isotopes pass through the pores and more of the heavier ²³⁸U isotopes remain within the barrier. The enriched stream is repressurized and reheated, then passed to another stage. A total of 1,200 of these stages is required to achieve the 3% concentration of ²³⁵U needed for light water reactors.

Source: Department of Energy, "Gaseous Diffusion Program," 1978.

cross-sectional area of diffusion barrier, a power density about as large as that of a blast furnace. Even with all this power, it takes 15,000 kilowatt-hours to produce a single kilogram (2.2 lbs) of enriched uranium. (Uranium enrichment is quantified in "separative work units." Usually, about 6 SW Us go into producing 1 kilogram of reactor-grade fuel.)

Department of Energy gaseous diffusion plants are spread over 270 acres across three states, and together consume a significant fraction of the output of the Tennessee Valley Authority. Rabelais' Gargantua would have been impressed. It's no wonder that shortly after the discovery of tunable organic dye lasers that operate in the visible part of the electromagnetic spectrum, researchers began to use them to experiment to develop more advanced methods of isotope separation and other chemistry processes.

'Non-equilibrium' processes

According to data published by the Department of Energy, the fully developed atomic vapor laser isotope separation (AVLIS) process requires only 3% of the electric power that gaseous diffusion requires, to produce enriched uranium; in other words, its rate of transformation of electric energy into product is about 30 times greater; and Livermore scientists write that AVLIS can perform the enrichment in a single step, with an expected plant throughput (output per acre) 50% greater than even upgraded gaseous diffusion plants.

What mode of physical action does AVLIS employ to achieve these results? An electron beam vaporizes natural uranium vapor which is then irradiated by coherent orange light of three distinct wavelengths. Only the U-235 atoms

FIGURE 2
Differences in wavelengths of light absorbed by uranium isotopes
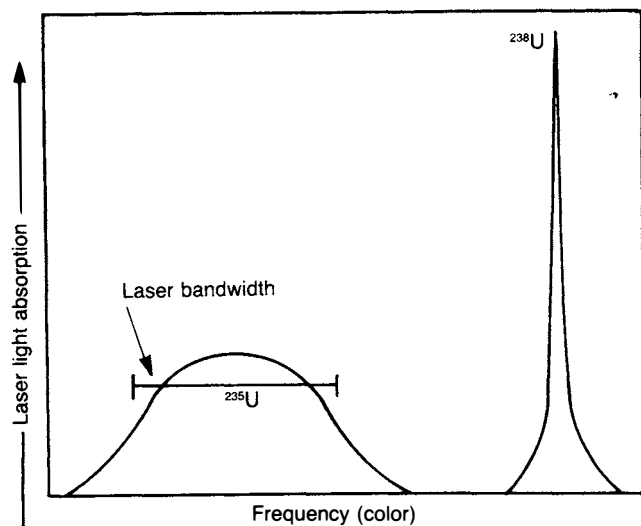
Source: Lawrence Livermore National Laboratory, "Laser Applications: Isotope Separation," 1982.

FIGURE 3
Schematic of AVLIS process
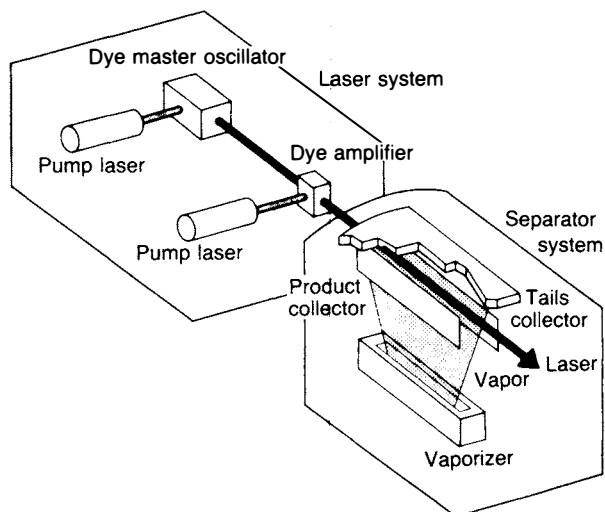
Source: J.I. Davis, "Lasers In Chemical Processing," Lawrence Livermore National Laboratory, April 15, 1982, UCRL-53276.

absorb this light and are excited to ionization, because of the difference or isotope shift in the frequencies (or wavelengths) of light that U-235 and U-238 absorb (see **Figure 2**). This selective excitation of the desired U-235 isotope, is an example of a "non-equilibrium" process. The laser action excites only the less than one percent of the feed that is U-235. The U-238 atoms remain "cold"; they are transparent to it. The ionized atoms are withdrawn by an electromagnetic field (see **Figure 3**).

AVLIS is effective because it employs a mode of action that, to use a phrase coined by Lyndon H. LaRouche, Jr., is of greater "relative coherence of least action" than the gaseous diffusion process. The action of the AVLIS lasers results in a greater selectivity of physical action, and thus a greater selectivity of isotope separation.

"Selectivity" is a parameter that has been developed out of work on nonlinear laser spectroscopy, to compare the effectiveness of various methods to accomplish a chemical transformation. Livermore scientists report that the theoretical selectivity ($\beta - 1$) of atomic vapor laser isotope separation, is 10 million (compared to 0.0043 for gaseous diffusion), and that selectivities as high as 20,000 have been achieved in the laboratory. In actual uranium enrichment plant operation, a selectivity of about 15 will be used (7,500 times greater than that of gaseous diffusion plant operation) in order to maximize throughput.

An additional metric for the development of technology

Through discussions with several chemists at the national labs, *EIR* has applied the metric of selectivity developed in

FIGURE 4
Model of physical-chemical action
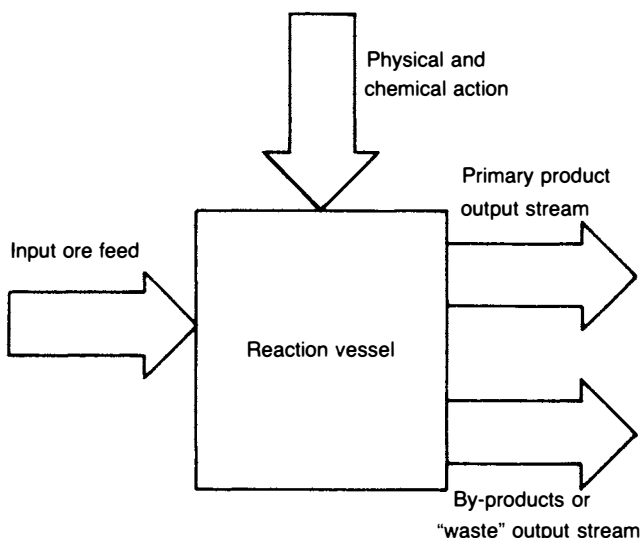
nonlinear laser spectroscopy, to measure the development of technology in iron reduction and aluminum smelting and other chemical concentration processes. The results further document just how revolutionary will be the changes induced in industrial processes by the widespread introduction of laser and plasma chemistry through the Mars colonization mission.

We begin with a simple model of physical-chemical action (see **Figure 4**). A material or ore carrying a substance we wish to concentrate (such as U-235), is fed into a reaction vessel in which various modes of physical and chemical action are applied to concentrate it into a primary product output stream, physically separable from by-products or "waste."

For example, in iron reduction, iron ore, pellets and sinter, bearing iron oxides, are fed into the blast furnace (the reaction vessel) with coke whose carbon serves as both a fuel and a reducing agent, and limestone which fluxes impurities out of the iron and forms a slag. Air is blown in at the bottom of the furnace to provide oxygen for combustion of the coke. Molten iron is tapped from the bottom of the furnace and is separable from the molten slag because the slag is lighter and floats on top of it. The principal forms of action are heat, oxidation-reduction reactions, and the fluxing of the impurities. All reactions take place in a condition of thermal equilibrium of the reactants.

Selectivity is defined in this or any other process as the ratio of the purity of the product to the impurity of the input feed material, or more precisely, the ratio of the concentration of the desired material (iron metal) in the primary product output (molten pig iron) to the concentration of all other molecules, elements or isotopes in it, divided by the ratio of the concentration of that desired material to that of all other molecules, elements or isotopes in the input feed (iron ore).

For example, in 1973 Republic Steel Co.'s Cleveland No. 5 blast furnace produced iron of 93.6% purity, from ore, pellets, and sinter of 62% iron. The ratio of the iron to other elements in the product was 14.7; that of the iron to other elements in the feed was 1.65. The selectivity is the ratio of these ratios, or 8.9.

Table 1 shows that from the Civil War until World War I the selectivity of the blast furnace only doubled, and has remained at that level since 1920. **Table 2** shows that the selectivity of aluminum smelting has not even doubled since its commercialization in the 1890s.

Both ironmaking with the blast furnace and aluminum reduction, excite all elements in the input feed equally—the materials are in thermal equilibrium. Under these conditions, little could be done to improve their selectivity by a significant factor. This places a limit on process throughput (as will be made clear in the following section). If the selectivity of iron reduction is not improved, the throughput of the furnace cannot be increased without compromising the quality of the product—unless the ore is fed in pre-concentrated or pre-reduced, and this is exactly what U.S. ironmakers did following World War II, with use of iron ore concentrate pellets and sinter.

Table 3 compares these thermal chemical processes with the two isotope separation processes we have discussed in terms of their primary modes of physical action and reagents. In the case of laser isotope separation, the primary reagent is photons.

As presently understood, the progress of chemical action under conditions of thermal equilibrium is rigidly determined

TABLE 1
Selectivity in iron production, 1867-1970

| Blast furnace | Date | Ratio of iron to other elements | | Selectivity |
		Product	Ore Feed	
Fletcherville, Pa. charcoal	1867	12.9	2.13	6.1
Brazil, Ind. bituminous	1869	11.5	2.13	5.4
Fletcherville, Pa. anthracite	1873	14.5	2.13	6.8
Chicago South No. 6	1919	13.3	1.33	10
Jones & Laughlin	1950	12.3	1.37	9.0
Republic Gadsden No. 2	1970	12.8	1.17	10.9
Republic Cleveland No. 5	1970	14.7	1.65	8.9

Sources: *Journal of the Franklin Institute,* 1892; American Institute of Mining Engineers, *Transactions,* 1873; *Ironmaking Proceedings,* 1950, 1970; Cox, *Geology of Indiana,* 1869; Carnegie Steel Co., *The Making, Shaping and Treating of Steel,* 1920.

Selectivity of commercial aluminum production, 1896-1970

| Date | Ratio of aluminum to other elements | | Selectivity |
	In Product	In Alumina feed	
1896	24	0.34	72
1925	99	1.1	90
1970	124	1.1	113

Sources: Joseph W. Richards, *Aluminum*, 1896; Robert Anderson, *Metallurgy of Aluminum*, 1925; P.C. Varley, *Technology of Aluminum*, 1970.

TABLE 3
Forms of action in several industrial processes

Process	Action, reagents
Blast furnace iron reduction	Combustion, oxidation-reduction reactions, fluxing
Aluminum reduction	Electric power, cryolite electrolytic catalyst
Gaseous diffusion isotope separation	Pumping and compressing heated gas
Laser isotope separation	Coherent radiation

by reaction pathways, reactivities and other parameters derived from thermodynamics. Laser processes enable us to "override the thermodynamics of a system," as Danen put it, by the selective action of coherent radiation.

If such "non-equilibrium" processes as atomic vapor laser isotope separation represent the technologies of the future, then in the future thermodynamics will be considered irrelevant in science, technology, and industry. The Mars colonists will regard it as outdated.

Indeed, with the use of the non-equilibrium plasma processes described in the Oct. 15, 1985 *EIR Quarterly Economic Report,* the selectivity of ironmaking will exceed 1,000 in plant operations, and productivity and throughput will zoom.

Until the advent of "non-equilibrium" processes, the metric of average energy flux density, the quantity of energy applied per second through a surface or volume where work is performed, served as a good measure of the development of the level of technology of industrial processes based on thermal equilibrium chemistry.

The average energy flux density of the AVLIS process, however, is at most 3% of that of the outdated gaseous diffusion process. The reason for this is simply that the several kilowatts of average power that irradiate the one-meter cross-

section of uranium vapor, is only required to deposit energy on less than one percent of the vapor. Selectivity of action ("relative coherence of least action") must be added to our list of critical parameters of technology.

In addition, with laser industrial processes, we have a significant difference between average and peak energy flux density. In iron reduction, for example, these are the same; the blast furnace operates continuously at the same energy throughput. In AVLIS, however, with an average energy flux density (or power density) of only about four kilowatts per square meter of uranium vapor irradiated, the peak power density of the short laser pulses is 5000 kilowatts per square meter, or about 30 times that of gaseous diffusion.

We proceed now with a more detailed discussion of the basis for the "non-equilibrium" selective action of lasers in chemistry.

Principles of laser isotope separation

Table 4 shows theoretical, laboratory and plant operation values for selectivity for the gaseous diffusion and atomic vapor laser isotope separation methods. For gaseous diffusion, the theoretical value is based on the difference in mass of the two isotopic species of uranium hexafluoride gas pumped through the separation stages. For AVLIS, the theoretical value is based on differences in the absorption spectra of the two species of uranium metal, and on the narrowness of the absorption lines.

Figure 2 illustrates the difference in the ground-state absorption spectra for U-235 and U-238. The U-235 absorption line is broken up into eight narrow, hyperfine absorption lines not shown in the figure. For one transition of U-235 from the ground or unexcited state to a state excited by absorption of a 0.64 micron (orange) photon, the difference or isotope shift between the absorption lines (about 9 gigahertz), and the narrowness of the U-235 hyperfine absorption lines (about 0.25 gigahertz), result in a high theoretical selectivity of over 1,000 for this single step transition discussed in detail by the AVLIS staff in a 1982 article in *Photonics Spectra.* AVLIS uses a series of three steps of photo-excitation of U-235, each step with approximately the same selectivity, resulting in a total theoretical selectivity equal to the product of the selectivities achieved in each individual step, for a total of at least 10 million, they report.

This high selectivity is not unusual for atomic laser isotope separation. V.S. Letokhov reports in his widely praised *Nonlinear Laser Chemistry* (Springer-Verlag, 1983) that the isotope shifts for the lanthanide and actinide groups of elements (of which uranium is one) are so large that total multistep selectivities of 10 billion are theoretically possible. Selective excitation of one isotope from the unexcited to an excited state (where it has absorbed energy), produces an even larger isotope shift between the excited U-235 and the unexcited U-238.

Figure 5 shows the sequence of excitation of U-235 in the AVLIS process, through a ladder of three distinct energy

TABLE 4
Parameters of uranium isotope separation methods

	Gaseous Diffusion	Atomic vapor Laser IS (AVLIS)
	Parameters of physical action	
Action of Separation*	Pumping and compression	3 0.6-micron visible photons
Selectivity ($\beta - 1$)		
theoretical	0.0043	10,000,000
lab measurement	NA	20,000
plant operation	0.002	10–20
No. of separation stages required	1,200	1
Output per year (millions of SWUs)	9.3	12
Output per acre (1000 SWU/acre)	100	150
	Parameters of energy use	
Average energy flux density (kW/m²)	120-180	4
Peak energy flux density	120-180	5000
Energy consumed per unit output (kWh/SWU)	2500	65
Energy transformation rate (SWU/1000 kWh)	0.4	15.4
Electric power conversion efficiency	More than 90%	Less than 0.5%

Sources: *Fusion,* December 1981; V.S. Letokhov, *Nonlinear Laser Chemistry,* Springer-Verlag, New York, 1983; Glasstone, *Principles of Nuclear Reactor Engineering*; J. Davis and J. Paisner, "Science, Technology, and the Industrialization of Laser-Driven Processes," Lawrence Livermore National Laboratory, May 1985, UCID-20448; Department of Energy, "Gaseous Diffusion Program," 1978.

*Uranium enrichment is quantified in "separative work units." Usually, 6 SWUs go into producing 1 kilogram of reactor-grade fuel.

FIGURE 5
Baseline process

Source: J. Davis and J. Paisner, "Science, Technology, and the Industrialization of Laser-Driven Processes," Lawrence Livermore National Laboratory, May 1985, UCID-20448.

transitions, each corresponding to the absorption of a photon of a wavelength specific to the transition. The corresponding transitions for U-238 are also shown. Notice that the heights of the transition differ between U-235 and U-238; the spacings between the dotted and solid lines on the right represent the isotope shifts. If the absorption line spectra and widths remain constant, then theoretically, if the concentrations of U-235 and U-238 in the uranium feed were equal, AVLIS could deliver photons to the uranium vapor so that for every 10 million U-235 atoms in the separated product, only one U-238 atom would be mixed in.

In practice, this large theoretical selectivity is limited by several factors.

1) Doppler broadening ("detuning") of the absorption lines. The movement of individual atoms or molecules in a gas shifts their absorption lines relative to the frequencies at which they would absorb light if the atoms or molecules were at rest. This Doppler-shifting of the absorption lines of individual atoms or molecules, results in a broadening of the absorption lines of the gas as a whole. At room temperature, the overlap in the infrared absorption spectra of U-235 hexafluoride and U-238 hexafluoride makes them almost indistinguishable. Scientists at Los Alamos National Laboratory had to cool the gas under low pressure to produce the distinct absorption lines shown in **Figure 6** for the two isotopes.

The AVLIS process minimizes Doppler broadening by generating the atomic vapor in a stream that moves perpendicular to the laser radiation, thereby reducing effects from variation in atomic vapor velocity relative to the laser light.

2) The laser bandwidth, the spread of frequencies it produces, should match the width of the absorption line of the isotope desired for excitation. Otherwise, it may excite the undesired isotope. This is entirely a technological problem in the development of the coherence of lasers. The bandwidth of the AVLIS tunable dye lasers is about 1-3 gigahertz.

3) Magnetohydrodynamic effects limit practicable selectivities for high input gas densities. Extracting the ionized U-235 atoms from the feed gas of natural uranium, necessarily pulls many U-238 atoms along as well, as a result of "charge sharing" among the ionized U-235 and the un-ionized U-238.

James Drummond has shown that with only 1% ionization of the aluminum metal in a gas of dissociated aluminum oxide, there is enough "charge sharing" that as much as 90% of the aluminum can be extracted from the aluminum and

Absorption lines for two uranium isotopes
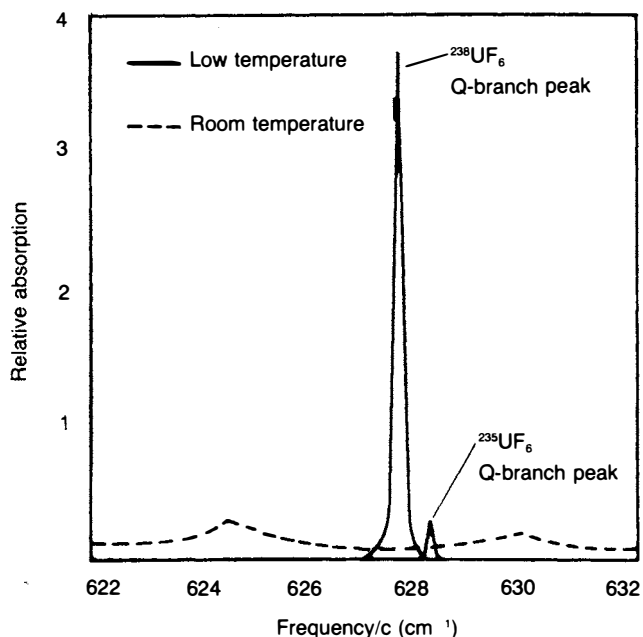
The v_3 absorption band of expansion-cooled natural-assay UF_6 exhibits narrow, distinct Q-branch peaks for $^{238}UF_6$ and $^{235}UF_6$. In contrast, the room-temperature band is broad and the isotopic features are merged. (For clarity the $^{235}UF_6$ peak is increased in height. The Q-branch peak heights for a sample containing the natural mixture of uranium isotopes are in the ratio of about 140 to 1.)

oxygen stream with magnets (U.S. patent 3,942,975). Atomic physicists call this effect "charge exchange."

Because of Doppler broadening and this MHD effect, selectivities achieved in the laboratory are considerably lower than the theoretical values.

Using waste as ore

At low gas densities, Livermore scientists have measured selectivities of 20,000 (see **Figure 7,** which shows the mass spectrum from such a separation experiment). Since it is only necessary to employ a selectivity of about 4.5, to enrich natural uranium in a single step from 0.71% U-235 to 3.2% U-235 uranium nuclear fuel, AVLIS can draw on the huge potential gradient between the selectivity it has achieved at low densities in the lab and that required in a plant, in order to operate at high gas densities (and therefore throughputs) in producing nuclear fuel. This also permits AVLIS to use as feed, spent uranium ore left over from years of gaseous diffusion plant operation, to produce enriched uranium fuel. The U-235 content of this depleted ore is only 0.2%, but a plant operating at an average selectivity of 15 can produce enriched fuel from this depleted ore, which was previously regarded as waste. Livermore plans for AVLIS to operate in

this mode at a selectivity of about 15. Nonetheless, even at this relatively low operating selectivity (for AVLIS), no photons are wasted in exciting U-238, according to Livermore scientists; the U-238 atoms that constitute 96.8% of the enriched product are drawn into the output stream by "charge sharing."

Another feature of the AVLIS process that shows its effective use of the principle of least action, is its method of ionizing uranium. The cross-section (or probability) for the direct ionization of atoms or photodissociation of molecules is very small, compared to the cross-section for absorption of non-ionizing photons. As a result, a process that directly ionizes atoms with light, will have a low selectivity since selectivity is directly related to reaction cross-section. AVLIS circumvents this problem by driving the atoms to highly excited "Rydberg" states which are then ionized by the action of an electromagnetic field.

It might be argued that since the absolute values of the selectivity of the blast furnace (about 9-11) are not much lower than those of the selectivity expected in plant operation in the atomic vapor laser isotope separation process (15), and indeed the selectivity of aluminum electrolysis is much higher (about 113), that therefore laser chemistry will not introduce a significant advantage to industry.

First of all, AVLIS has shown that it can tune its selectivity up and down from whatever low value to about 20,000. Uranium enrichment plant operation, only requires a selectivity in the range of 5 to 15. Higher selectivities would produce a nuclear fuel product enriched in U-235 more than desired. Some U-238 would have to be mixed in with the product to produce commercial nuclear fuel.

Secondly, the argument overlooks the fact that uranium isotope separation is intrinsically more difficult than either iron or aluminum reduction. We can crudely estimate the comparative difficulty of separating U-235 from U-238 with that of separating iron or aluminum from oxygen by calculating the ratio of the mass differences involved; this is 3/238 for uranium separation, 40/56 for iron reduction, and 11/27 for aluminum reduction. The ratios of these ratios (40/56 to 3/238 = 57; 11/27 to 3/238 = 32) provide a rough idea of how much easier the latter two processes are than the former.

Role in Mars colonization

Laser isotope separation is more than a demonstration of the technological revolution that lies ahead of us in industrial chemistry. It will be an integral part of the Mars colonization effort itself. Production of deuterium and tritium fusion fuel in the quantities required, will demonstrably require advanced laser isotope separation technologies to extract them from natural sources, such as water.

Laser deuterium and tritium isotope separation are under development at Atomic Energy of Canada and Ontario Hydro, for the production of heavy water (D_2O) for the Canadian Deuterium-Uranium (CANDU) nuclear power reactor, and for the separation of tritium bred from heavy water in oper-

FIGURE 7
Experimental verification
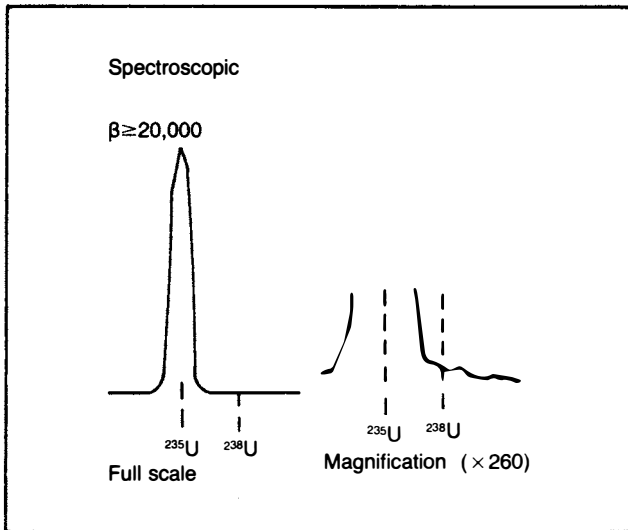
Source: J. Davis and J. Paisner, "Science, Technology, and the Industrialization of Laser-Driven Processes," Lawrence Livermore National Laboratory, May 1985, UCID-20448.

ating CANDU reactors. Presently, a one gigawatt CANDU reactor requires 800 metric tons of heavy water to serve as a moderator of the nuclear chain reaction. With present deuterium separation technology, this need amounts to 15 to 20% of a plant's *capital cost*, or about $200 million. Since 800 metric tons of heavy water includes 160 tons of deuterium, present technology produces deuterium at a cost of over $1,250,000 per metric ton.

A single manned flight to Mars with the fusion rocket designed by Roderick Hyde of Lawrence Livermore National Laboratory, requires about 1,000-2,000 tons of deuterium fuel for a total cost of over $2 billion per flight. The Mars program demands that this cost be brought down, and it will be, through laser isotope separation. This demand will get the AVLIS program moving again after years of lethargy induced by the fall-off in demand for commercial reactor fuel.

The experience of atomic vapor laser isotope separation demonstrates that laser chemistry will revolutionize industry in a way comparable to the introduction of central electric power generation. Rapid development of the technologies required for large-scale industrial laser chemistry, is required by both the Mars colonization program and the Strategic Defense Initiative. In particular, the Mars program and the SDI will confer upon industry high-power tunable free electron lasers, the tool of the future, which will produce coherent radiation at the wavelengths required to achieve least action in industrial processes. The tunable dye laser without which AVLIS would not have been possible, sho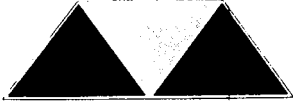ws us the great promise of this technology.