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Laser Enrichment of Uranium: The Proliferation Connection

Serious policy issues are raised by the prospect of small, efficient uranium enrichment plants.

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The release in recent months of a considerable amount of technical information on the potential use of lasers to enrich uranium has given rise to cries of alarm from a number of sources, with the arms control "community" leading the way. In his calm and accurate review Metz (*1*) quoted an unnamed "weapons scientist" as fearing that the new technology might "enable people to 'build bombs in their basements.' " The *New York Times* of 27 June 1976 quoted Dr. Fred C. Iklé, head of the U.S. Arms Control and Disarmament Agency, as fearing that the "spreading [of] information about this technique could make it easier for other nations to circumvent our controls against nuclear proliferation" (*2*). Iklé was responding to the concern of Professor Paul Doty, Jr., a biochemist at Harvard, who was "disturbed" by what he saw as an irresponsible release of highly sensitive information. These reactions have resulted in a great sensitivity on the part of U.S. government agencies to the danger of the release of any more information to the public, and a very tight lid has been clamped on all activities in this area. Some scientists feel that this reaction has gone too far and that it threatens to interfere with basic research in a number of areas of laser photochemistry and isotope separation quite unrelated to uranium enrichment (*3*).

Not surprisingly, people became alarmed when it first became known that the new technology might lead to nuclear proliferation. There is a great deal of anxiety these days about the potential for nuclear weapons proliferation, and the alleged simplicity and cheapness of this new laser technique seems to have removed whatever tenuous restraints still remained on the spread of nuclear weapons, not only to medium-sized and small countries but possibly even to terrorist groups or criminals as well. The possibility of a quick and easy method of producing highly enriched ^{235}U from natural uranium seemed to pull the rug out from under those people who were laboriously trying to design an international system of safeguards against the diversion of plutonium from the civilian nuclear industry to weapons production.

My own interest in this problem was originally motivated by the same sense of alarm expressed by the people quoted in the opening paragraph. Since then, my attitudes have undergone several modifications. An earlier draft of this article had the rather flippant subtitle "Let's keep our shirts on" and emphasized the obstacles associated with the development of the technology and what I saw to be the potentially high cost and technical complexity of laser enrichment facilities. However, reactions to this first draft by several people more knowledgeable in the area than I have caused me to reassess this conclusion somewhat. If I were to use the same metaphor, I might say that, while I am not yet about to tear off my shirt, it might be prudent to loosen a few buttons.

As this article was being written, I was acutely aware that, even if it correctly describes the situation which existed at some time in the past, that picture is almost certainly already obsolete. The secrecy which now covers all significant aspects of laser enrichment research makes it impossible for an outsider to obtain meaningful information and at the same time prevents an insider from saying anything in public except for the most impenetrable generalities. The only thing that seems certain is that research on lasers and on the materials-handling techniques required for laser enrichment is being vigorously pursued both in the United States and in other countries and seems to be making progress. For this reason it is essential that discussion of the policy implications of this research begin as soon as possible. I am hopeful that this article can provide a stimulus and a framework for this discussion.

My purpose in this study is to examine as objectively as possible the implications of laser enrichment of uranium for nuclear weapons proliferation. One thing my study does *not* do is to attempt to determine whether laser enrichment will ultimately prove economically competitive with other enrichment techniques on a large scale. Even those who have access to all of the classified and proprietary information are not yet in a position to do this. I will be interested here only in the question of whether this new technology threatens to alter significantly the situation with respect to the worldwide proliferation of nuclear weapons. To have such an effect, an enrichment technology would have to be considerably cheaper and less capital-intensive than existing technologies and should not be so technically sophisticated that a large, advanced research and development capability is needed for its creation. To the best of my knowledge, it remains an open question whether such an enrichment technology can be developed, but there are some things one can learn about its probable outcome simply by looking at the basic physical processes involved in laser enrichment.

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Some Definitions

The object of the enrichment process is to produce from a batch of natural uranium (99.29 percent ^{238}U, 0.71 percent ^{235}U) a product with a substantially higher percentage of ^{235}U. To produce fuel suitable for nuclear reactors moderated by light water, the percentage of ^{235}U must be increased by a factor of about 4, up to 3 percent; to produce a reasonably high-quality material for nuclear weapons fabrication, the percentage of ^{235}U should be on the order of 90 percent, more than 125 times the natural composition. The molar fractions of ^{235}U in the feed, product, and waste streams can be denoted by x_0, x', and x, respectively. As an example, for a plant producing 3 percent enriched uranium from natural uranium with a waste-stream assay or "tails assay" of 0.2 percent, the values would be $x_0 = 0.0071$, $x' = 0.03$, and $x = 0.002$. On the basis of these compositions and the fact that the total amount of ^{235}U is conserved throughout the process, it is easy to calculate the amounts of feed and waste material for a given amount of product material. In general, for each mole of product the number of moles of feed required and the number of moles of tails produced are given by:

$$\text{Feed} = \frac{x' - x}{x_0 - x}$$

$$\text{Tails} = \frac{x' - x_0}{x_0 - x}$$

In my example 5.49 moles of feed material are required to produce 1.00 mole of product and 4.49 moles of tails. On the other hand, to produce 90 percent enriched explosive material one would require 176 moles of feed for every mole of product. If 20 kilograms of ^{235}U are needed to produce a bomb, then roughly 3.5 metric tons of natural uranium would be needed for each bomb.

We can classify the enrichment process under one of two categories. The process can be a repetitive one involving many stages, each producing a very small enrichment, or it can be a "single-shot" process which produces small amounts of product which differ significantly in composition from the feed material. Most traditional methods of uranium enrichment have been of the first type. These include gaseous diffusion, centrifuges, and the Becker nozzle process (*4*). The electromagnetic separation process on which considerable work was done during World War II is of the second type, but it has never been shown to be commercially feasible. The laser enrichment technologies that I will discuss in this article are also of the second kind and do show some promise of being competitive with other large-scale enrichment technologies.

All of the processes can be characterized by a parameter called the "selectivity factor," defined by the equation

$$\alpha = \frac{\Delta n_1}{\Delta n_2} \frac{n_2}{n_1}$$

where n_1 and n_2 are the numbers of moles of the desired and undesired isotope, respectively, in the feed material, and Δn_1 and Δn_2 are the incremental amounts of these species added to the product stream in a given step. Obviously, α must be greater than 1 in order for enrichment to occur. In general, the multistage processes are characterized by an α that is only slightly larger than 1 whereas the single-shot processes have much larger values. For example, gaseous diffusion has a theoretical α value of 1.0043 and in practice (*5*) achieves a value of only about 1.002. For the centrifuge method α values of about 1.25 have been assumed (*6*). On the other hand, proponents of laser enrichment believe that α values well in excess of 1000 may be obtainable with properly designed systems.

The requirements of land area, capital investment, and energy for multistage processes are enormous. Thousands of enrichment stages are required to produce weapons-grade uranium by gaseous diffusion and dozens by centrifuge. The energy required to produce a single fissionable ^{235}U nucleus for reactor fuel by gaseous diffusion is 3 million electron volts, or more than 4 percent of the usable energy produced by that nucleus in a reactor. The energy costs for centrifuges are projected to be about one-tenth of this [see (*1*), table 1], but both are many orders of magnitude larger than the thermodynamic lower limit of about 0.03 electron volt.

The use of laser enrichment techniques, it is hoped, will come considerably closer to the ideal than gaseous diffusion or centrifuges. Because a laser is a source of highly monochromatic light which can be tuned with great precision, it is possible to think of utilizing the small isotope shifts in the absorption spectra of uranium atoms or molecules to achieve selectivities of greater than 1000. The tunability of the laser may allow the enrichment to be completed in a single stage, eliminating the energy-consuming pumping and heating requirements of diffusion and centrifuges and saving uranium by reducing the tails assay. The single-stage process would also allow for a much more compact enrichment plant, saving on land area demands and capital investment. These hopes for a more economic means of enriching uranium coupled with projections which indicate a rapidly rising demand for new enrichment facilities have led to very active research and development programs in the United States, the Soviet Union, Israel, France, and possibly other countries.

In the United States the development of laser enrichment is being pursued along two quite distinct tracks. Jersey Nuclear–Avco Isotopes, Inc. (*7*) and a group at Lawrence Livermore Laboratories are working with atomic uranium. Research on molecular uranium hexafluoride (UF_6) is being pursued by a group at the Los Alamos Laboratories and another group at Exxon Research Laboratories (not connected with Jersey Nuclear–Avco). Each of these methods has its virtues and its defects, and these techniques seem to be to a great extent complementary. Therefore, the two sets of research groups have little to offer each other in the way of help, and as one talks with scientists involved in both programs one quickly learns that a rather intense rivalry prevails.

Laser Enrichment with Atoms

Laser enrichment experiments on atomic uranium vapor have already produced enriched samples, albeit in very small amounts. Experiments at the Lawrence Livermore Laboratories (*8*) have been developed to produce ^{235}U ions at the rate of 2×10^{-3} gram per hour, at which rate it would take several hundred years to accumulate a critical mass of pure ^{235}U. Considerable efforts are being made to increase this production rate by many orders of magnitude in order to make it commercially practical and apparently some progress is being made, since at this writing Jersey Nuclear–Avco is still eager to proceed with its plans for an intermediate-sized test facility (*9*).

The uranium atom has six valence electrons, and the ground state configuration of the atom is $5f^36d7s^2$. This electronic configuration leads to an extremely complex optical spectrum consisting of "over 900 identified energy levels, 9000 classified transitions and perhaps as many as 300,000 visible lines" (*10*, p. 112). It would seem to follow from this complex spectrum that there should be no real problem in finding a visible or ultraviolet laser which can be tuned to an appropriate transition in uranium vapor.

In atomic uranium the major contribution to the isotope shift is produced by the difference in size between the ^{235}U and ^{238}U nuclei. The nuclear mass difference and differences in hyperfine interactions contribute lesser amounts. The size of the isotope shift varies between 0.005 and 0.009 nanometer near a wavelength of 420 nanometers [see (*10*), table 1], which corresponds to shifts of between 0.28 and 0.51 reciprocal centimeter at 23,800 reciprocal centimeters. So the tuning of the existing laser must be precise and stable to roughly one part in 10^5. This precision requirement does not seem to present any problems, in view of the already high degree of precision and stability of most lasers.

In the atomic enrichment process most often discussed, molten uranium is heated in an oven to about 2500°K. The atomic vapor emerges in the form of a long, thin ribbon (*11*) (Fig. 1) into a highly evacuated region where it can be illuminated by two visible or near-ultraviolet lasers. One laser is tuned to a transition from the ground state of uranium to an excited state roughly halfway up the ladder to ionization. This is the isotopically selective step, and it is hoped that very high selectivities will be achieved at this step.

The purpose of the second laser is to boost the excited ^{235}U atoms to a level just below the ionization limit. This step need not be isotopically selective, and in principle the second laser could be used to ionize the atom directly. But ionization cross sections are generally about 1000 times smaller than resonant excitation cross sections, and so it is far more efficient to use a resonant transition to excite the atom to a state just below the ionization level and then to use either a static electric field or an infrared laser pulse to pull the electrons off the atoms (*12*). Once the atoms are ionized, they can be separated from the neutral atoms in the beam by the use of electric or magnetic fields, or both.

The major limiting factor in the above process is the density of atoms in the uranium "ribbon." There is an upper limit on the density and therefore on the rate of production of enriched uranium, because both excitation energy and ionic charge are very easily transferred to other atoms in collisions. Such collisions must be kept to a minimum if a high selectivity is to be obtained. According to Letokhov and Moore (*11*, p. 138), the cross section for charge exchange scattering is roughly 10^{-14} square centimeter. If a product enrichment of 90 percent is desired, then the probability of charge exchange must be of the order of 1 in 10. Therefore, the mean free path of a ^{235}U ion must be ten times the thickness of the ribbon, which in turn is limited by the diameter of the laser beams and will typically be about 1 centimeter. The limiting density is given by the inverse product of the mean free path and the cross section and is therefore about 10^{13} atoms per cubic centimeter. Of course, if one wants a product with only 3 percent enrichment, then the odds that a ^{235}U ion escapes intact need only be about 1 in 30, corresponding to a mean free path of 0.3 centimeter and a density of 3×10^{14} atoms per cubic centimeter. But densities this large may result in self-lasing of the uranium atoms, a problem which I discuss in the section on obstacles to practical laser enrichment. Moreover, these estimates do not take into account other factors which degrade the selectivity, especially the mechanisms for capturing and processing the final product.

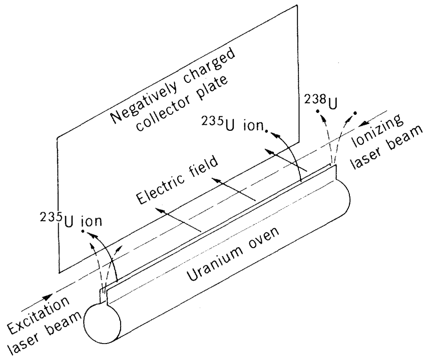


Fig. 1. Schematic of the atomic laser enrichment apparatus [adapted from figure 1 of (*29*)].

With a number for the atom density, we now need to get numbers for the length of the effective interaction region and the absorption cross section in order to estimate the number of atoms excited in each laser pulse. Typical resonant absorption cross sections (*10*) are of the order of 10^{-14} square centimeter, and so we can determine the interaction length of a photon by assuming that photons interact only with ^{235}U atoms (density, 10^{11} atoms per cubic centimeter, since only about one atom out of 100 atoms of natural uranium is ^{235}U). The interaction length is then 10 meters. If we assume that the laser beam has a diameter of 1 centimeter and that all the ^{235}U atoms in a cylinder 10 meters long are excited, then we will produce only 10^{14} excited atoms or 10^{-9} mole per pulse. This result implies that the laser must produce 10^{14} photons of wavelength 420 nanometers or 5×10^{-5} joule per pulse. This value is a very small energy, and it is not unreasonable to postulate energies 2000 times as large, that is, 0.1 joule per pulse. In this case the intermediate excited level would "saturate," that is, it would reach an equilibrium population in which just as many atoms were being stimulated to drop from the excited state to the ground state as were being excited upward from the ground state. If we assume that the two states have similar statistical weights, then we expect that under saturation conditions roughly half the ^{235}U atoms in the beam will be excited and half will be in their ground state.

In this situation the beam of photons will penetrate much farther into the vapor, a distance greater than the nonsaturation distance by a factor approximately equal to the ratio of the laser pulse energy to the energy absorbed in the nonsaturated case (*11*, p. 138). Since 0.1 joule is 2000 times as great as 5×10^{-5} joule, this beam could penetrate 2000 × 10 meters or 20 kilometers into the vapor. This obviously greatly expands the volume in which ionizations can take place and thereby increases the potential yield. Of course, no one has proposed a laser enrichment facility 20 kilometers long, but lengths of "hundreds of meters" have been mentioned [see (*1*), p. 1163], and there is always the possibility of designing a multiple-pass geometry for the laser beam. Clearly, the saturation technique is under active consideration. However, this technique also has its problems, and these I discuss in the section on obstacles to practical laser enrichment.

Another way to increase the production rate is to find a way to increase the density of atoms in the beam. Since the length of the interaction region is limited by practical considerations to a maximum of some hundreds of meters, only a fraction of the available laser power will be used for excitation if the density remains at 10^{13} atoms per cubic centimeter. A possible way to get around this limitation is to use the fact that charge exchange interactions between heavy atoms involve very little exchange of momentum (*13*). One can take advantage of this property by producing the ions in a strong electric field which accelerates them substantially before they undergo a charge exchange collision. (This electric field can presumably be the same one that generates the ions.) Then, even after an ion has been neutralized, it will retain the velocity transverse to the beam direction that it acquired as an ion. This maintenance of velocity will allow these neutral ^{235}U atoms to be separated from the rest of the beam, although they will have to be collected in a different way from the ions. Another way to get around the limitation of the amount of laser power available for excitation would be to attempt to increase the production

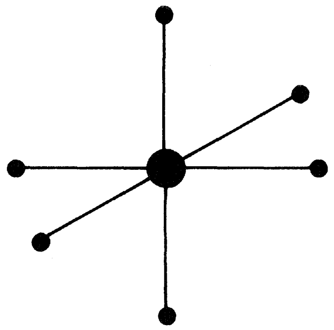


Fig. 2. Model of the UF_6 molecule. The uranium atom is at the center, and the molecule possesses the symmetry of a spherical top.

rate by using even higher-powered lasers with even faster repetition rates. The creation of new, high-powered lasers is an intensely active field of research, and so this possibility must be taken seriously.

To conclude this section I will imagine that the saturated beam method and higher densities are to be used and will compute the production rate which results. The assumptions and results of this calculation are summarized in Table 1. Let us imagine an atomic ribbon with a transverse length of 200 meters and a thickness of 1 centimeter. Let the total uranium density be 10^{14} atoms per cubic centimeter, which means 10^{12} ^{235}U atoms per cubic centimeter. Finally, I will assume a laser power sufficient to excite and ultimately ionize with each pulse roughly half the ^{235}U atoms within the beam volume. The result is about 10^{16} ^{235}U ions per pulse or, with a repetition rate of 1000 hertz, about 4 milligrams per second of nearly pure ^{235}U. Such a facility would produce about 0.34 kilogram per day of high-enriched uranium or enough for a single bomb every 2 months. It is clear that this calculation represents a very large and sophisticated facility. In addition, I have neglected a number of effects which will act to reduce the yield of such a plant and I have also assumed technological capabilities which do not yet exist. I will discuss in some detail below the other difficulties which arise from the use of the atomic methods described above.

Laser Enrichment with Molecules

Gaseous UF_6 is used in all proposed schemes for molecular enrichment, since this is the only compound of uranium with a sizable vapor pressure at reasonable temperatures. Figure 2 is a representation of the UF_6 molecule. The uranium atom is at the center, and the fluorine atoms are distributed around it in a highly symmetrical way. The fact that the molecule contains seven atoms and exhibits a high degree of symmetry leads to a very complicated spectrum of vibrational and rotational excitations. Theorists at Los Alamos have made substantial progress in understanding the details of the UF_6 spectrum (*14*), but a less sophisticated treatment will be sufficient to explain the laser enrichment process.

In the language of group theory, the UF_6 molecule belongs to the symmetry group O_h. Using this fact and standard techniques of group theory (*15*), one can show that the vibrational motions are described by six normal modes of oscillation. The most interesting vibrational modes from the point of view of laser excitation are those which involve motion of the uranium atom and which therefore produce an oscillating electric dipole moment. Only these modes undergo allowed (that is, strong) transitions from the ground state when excited by electromagnetic energy. There are two such frequencies in UF_6 and they are customarily given the names ν_3 and ν_4. Their values in wave numbers (*16*) are ν_3 = 626 reciprocal centimeters and ν_4 = 186 reciprocal centimeters. Both of these frequencies lie in the far-infrared portion of the spectrum. Indeed, ν_4 is so low that at room temperature one expects to find more molecules in the first excited state of ν_4 than in the ground state (*17*).

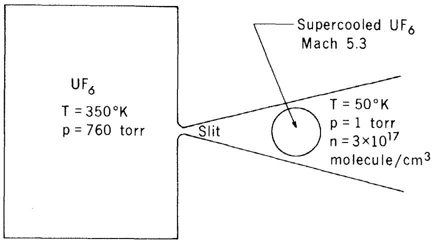


Fig. 3. Schematic of the supersonic expansion nozzle for the nonequilibrium cooling of UF_6.

The low energies associated with these transitions lead to two serious problems for laser enrichment in UF_6. The first problem concerns the creation of an infrared laser with the correct frequency, and I will delay discussion of this until the next section. The second problem is related to the high occupation numbers of the low-energy vibrational states at temperatures where UF_6 has a high vapor pressure. The fact that so many low-lying states are occupied means that it is impossible to find a single excitation frequency that will be absorbed by most of the molecules. The presence of these so-called "hot bands" reduces the efficiency of the process very drastically.

The second problem turns out to be easily solved, at least in principle, if warm UF_6 gas is passed through a supersonic nozzle (Fig. 3). The effect of the expansion is to convert most of the kinetic energy of random motion of the gas in the reservoir into kinetic energy of translational motion of the gas in the nozzle. As the gas accelerates through the nozzle, it becomes colder and the energy stored in the vibrational and rotational degrees of freedom of the molecules is reduced by intermolecular collisions in the narrow region just downstream of the slit. Some straightforward calculations based on the simple properties of an ideal gas undergoing a supersonic expansion (*18*) show that the vibrational and rotational temperatures can be lowered from 350° to 50°K over a distance of a few centimeters if the area of the nozzle expands by a factor of 32. The gas then has a Mach number of 5.3 and a pressure of about 1 torr, and, most important, 90 percent of the molecules are in the vibrational ground state.

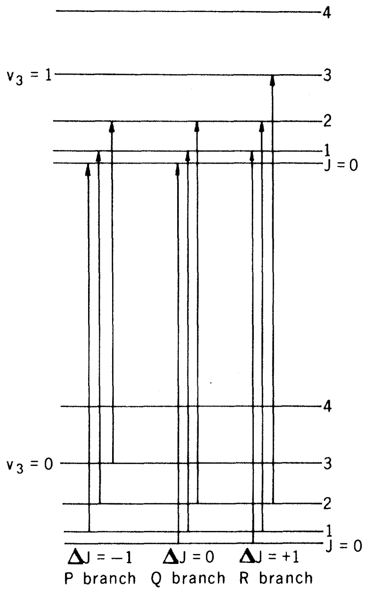
The molecules can now be illuminated by a laser beam which has been tuned to

Table 1. The assumptions made in determining the hypothetical maximum yields of high-enriched ^{235}U in the atomic and molecular laser enrichment processes. The time listed in the last column is that required to produce one critical mass (20 kilograms) of 90 percent enriched ^{235}U in a single facility, given the assumptions listed in the other columns. These times are almost certainly lower limits, since they depend on a number of optimistic assumptions about laser capabilities, product separation techniques, and system reliability. Real times could turn out to be one or two orders of magnitude larger, or even more.

Relevant cross section (cm^2)	Assumed density (cm^{-3})	Interaction volume (cm^3)	Laser energy per pulse (joules)	Pulse rate (hertz)	Time required to produce 1 critical mass (days)
		Atomic			
10^{-14}*	10^{14}	2×10^4	10^{-3}	10^3	60
		Molecular			
10^{-15}†	10^{17}	8×10^2	10^{-2} (infrared) 1 (ultraviolet)	10^2	3.5

*For charge exchange. †For vibrational energy exchange with another UF_6 molecule.

excite selectively molecules containing ^{235}U. The absorption feature referred to most in the literature on molecular methods is the "Q branch" of the ν_3 transition in ^{235}U. The meaning of this can be seen in Fig. 4, which shows schematically the ground vibrational state and the first excited ν_3 state (quantum number v_3), each with its associated rotational band (quantum number J). The selection rules allow transitions in which $\Delta J = 0, +1$, or -1. Transitions with $\Delta J = 0$ all require nearly the same energy, whereas those which change J require an energy which depends on J. These rules determine an absorption spectrum which looks something like that shown in Fig. 5. The Q branch is much stronger than the other peaks because it contains transitions from all occupied rotational levels of the ground state, whereas the height of each small peak in the P and R branches is proportional to the population of the given J state only. The finite width of the Q branch and the variations in spacings in the P and R branches are all due to small effects, well known to molecular spectroscopists but beyond the scope of the simplified discussion presented here.



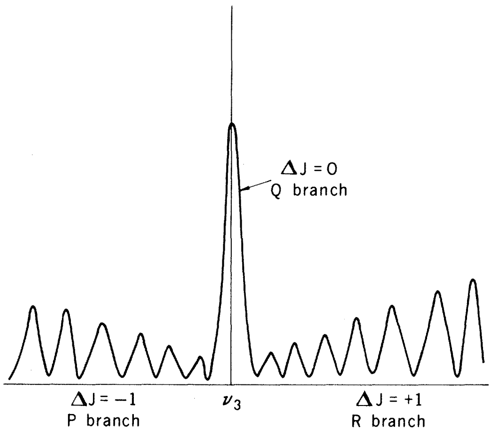


Fig. 4 (left). Representation of two vibrational levels with their associated rotational manifolds. The energy separations are not drawn to scale. Fig. 5 (right). Simplified representation of the ν_3 absorption band in UF_6.

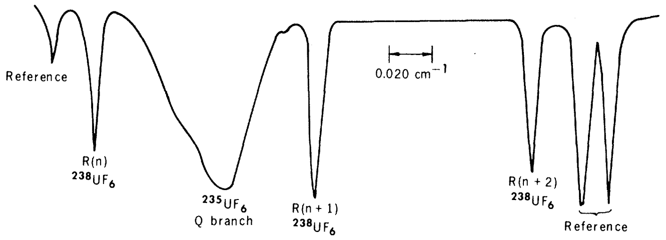


Fig. 6. High-resolution spectrum of a portion of the $^{238}UF_6$ R branch, showing the $^{235}UF_6$ Q branch.

The separation between the peaks of the P and R branches is related to the moment of inertia I of the molecule and is known from experimental measurements (*19*) to be about 0.1 reciprocal centimeter (see Fig. 6). The small value of the separation constant shows that the rotational levels associated with the ground state have very small energies and that even at 50°K a large number of them, at least 70, will be populated. In effect, then, 70 or more levels contribute to the Q branch absorption line whereas only one level contributes to each R and P branch line. This difference in origin explains the great difference in the heights of the lines.

Let us now suppose that the idealized spectrum of Fig. 5 is that of $^{238}UF_6$. Where shall we look for the Q branch line for $^{235}UF_6$? Since the ^{235}U atom has a slightly smaller mass than ^{238}U, we expect by analogy with a simple classical oscillator that the frequency will be slightly higher. So we expect to find the $^{235}UF_6$ Q branch somewhere among the R branch lines of $^{238}UF_6$. It is not possible to compute the isotope shift exactly, and the exact value of the $^{235}UF_6$ frequency is still a secret, but the value $\Delta\nu = 0.65$ reciprocal centimeter does appear in the published literature [see (*16*), p. 3576]. This result suggests that we can probably expect to find the $^{235}UF_6$ Q branch line between the R(6) and R(7) lines of $^{238}UF_6$ [R(6) is standard spectroscopic notation for the R branch line that originates on the $J = 6$ rotational level of the lower vibrational state]. Figure 6 shows the $^{235}UF_6$ line neatly centered between two $^{238}UF_6$ R branch lines, and so, if one could tune a high-powered laser to an accuracy of ± 0.02 reciprocal centimeter and concentrate most of its energy in a bandwidth of about 0.05 reciprocal centimeter, then one could obtain a very high degree of selectivity in the excitation mechanism.

In order to produce a clean and well-defined spectrum like that of Fig. 6, it is essential to flow-cool the UF_6 gas. This procedure will make possible, assuming that other problems can also be solved, a highly selective, single-shot enrichment process. There may, however, be other ways of overcoming the problem of the high thermal population of the lower vibrational levels without supercooling the gas. For example, one might preexcite the UF_6 by a nonselective process to a state above the thermally populated region and then use an isotopically selective laser to excite the ^{235}U to an even higher state. It may also be possible to dispense with flow-cooling if one is willing to settle for low selectivities and use several enrichment stages. It could turn out that a multistage process in which uncooled gas is used is easier to implement than a single-stage process with flow-cooling. The program at the Exxon Research Laboratories may be concentrating on methods in which warm UF_6 is used (*20*).

Thus far I have been discussing only the first step of the molecular isotope separation process, the selective excitation of $^{235}UF_6$ molecules to their first vibrational state. However, this procedure in itself does not provide a way of segregating the excited molecules; considerably more energy must be pumped into the molecules to get them to dissociate. There are two quite different techniques being explored to accomplish this step (*21*). The first is similar in concept to the atomic methods discussed above. With this method an ultraviolet laser is used to excite an electron transition in the molecule which leads to dissociation. In the second method an intense pulse of infrared laser light drives the molecule up through its vibrational manifold to dissociation. This latter method has attracted a great deal of attention during the past year since it was revealed that intense infrared radiation from a carbon dioxide (CO_2) laser can cause isotopically selective dissociation of a number of complex molecules (*22, 23*). However, the results of these experiments have been difficult to interpret, and there is no way to extrapolate the published data to UF_6.

Since it is not necessary for either of these secondary processes to be isotopically selective, the primary demands on the ultraviolet or infrared lasers are related to their energy output and pulse repetition rates. In both cases considerably higher powers are required for the molecular than for the atomic processes because much larger numbers of molecules can be processed in the same period of time. This high power requirement follows from the fact that the density restrictions seem to be less severe for molecules than for atoms; this less severe density restriction in turn depends on the much lower cross section for loss or exchange of vibrational energy in molecules than for exchange of ionic charge in atoms.

It is difficult to be quantitative about these statements without specific data on the UF_6 molecule. Presumably the gathering of such data is one of the primary tasks of the current research and development effort. We can, however, make some reasonably reliable order-of-magnitude estimates based on properties which seem to be shared by most molecules on which experiments have been done. Since sulfur hexafluoride (SF_6) has been the most studied and is structurally analogous to UF_6, I will concentrate on it.

Lyman and Rockwood (*23*) have displayed a graph of the vibrational relaxation times for SF_6, from which one can determine a rough value for the cross section for vibrational energy exchange with another SF_6 molecule. This value is of the order of 10^{-15} square centimeter, and it is convenient to assume that this value is applicable to UF_6 as well. If we are working with supercooled UF_6 which has been expanded adiabatically to a temperature of 50°K and a pressure of 1 torr, and if we assume that this can be done without condensation of the vapor taking place, then the number density can be shown to be 3×10^{17} molecules per cubic centimeter. The mean free path for vibrational exchange is therefore 3.3×10^{-3} centimeter. At a temperature of 50°K the average speed of the molecules is about 6×10^3 centimeters per second, and so the average lifetime of a vibrational excitation is 500 nanoseconds. Therefore, if we use a pulse length of 50 nanoseconds for excitation and dissociation, we can reduce the probability that an excited $^{235}UF_6$ will transfer its excitation energy to a $^{238}UF_6$ to 1 in 10. This situation is then analogous to the first two stages of the atomic process, and the dissociated molecules will be 90 percent ^{235}U. But the dissociated product must still be separated physically from the undissociated material, and it is clear that substantial recombination could occur if the recombination probabilities for UF_5 and F are high. There are also other possible selectivity-degrading reactions, and these I discuss in the next section.

However, if we assume for the moment that these separation problems can be solved and that no further degradation of the selectivity will take place after dissociation, we can use the above number density to estimate the necessary laser powers and potential yields. The absorption cross sections in UF_6 for the ν_3 transition (*24*) is about 6×10^{-18} square centimeter. With a total UF_6 number density of 3×10^{17} molecules per cubic centimeter we will have a $^{235}UF_6$ density of 2×10^{15} molecules per cubic centimeter, and so the photon interaction length will be about 80 centimeters (assuming that photons are absorbed only by $^{235}UF_6$). A longer path length can be obtained if the transition is saturated, and the pulse energy density needed to do this is found from the photon energy $\hbar\omega$ and absorption cross section σ as follows [see (*11*), p. 136]

$$E_{sat} = \frac{\hbar\omega}{2\sigma}$$

For the absorption in UF_6 at 628 reciprocal centimeters this energy is equal to 10^{-3} joule per square centimeter.

It is interesting to compare this figure with one given by Birely *et al.* (*25*) in an estimate of future laser needs for enrichment. They would like to have a 10-millijoule infrared laser, which would imply an irradiation depth of the order of 8 meters with a beam area of 1 square centimeter and the number densities we have been considering. The energy demands for the ultraviolet laser are not difficult to determine, if we assume that roughly one ultraviolet photon will be needed for each infrared photon. The pulse energies are then simply proportional to the photon energies. Thus we require the ultraviolet laser to be able to deliver on the order of 100 times the infrared energy or about 1 joule per pulse.

Let us assume that such lasers become available and ask how long it would take to produce 20 kilograms of 90 percent enriched ^{235}U—enough for one bomb (*26*). I will also make the very unrealistic assumption that every molecule that is dissociated is a part of the final product. If all the $^{235}UF_6$ molecules in a volume of 800 cubic centimeters are dissociated by each pulse, we obtain 1.6×10^{18} molecules per pulse. If we want 20 kilograms, this is about 80 moles or 5×10^{25} molecules, which means that 3×10^7 pulses will be needed. If the lasers can be run at a pulse rate of 100 pulses per second, the time necessary to produce 20 kilograms of ^{235}U would be 3×10^5 seconds or about 3.5 days. The lasers would be operating at power output levels of 1 watt for the infrared and 100 watts for the ultraviolet. Even if efficiencies of only 1 percent are finally obtained, this result still implies power dissipations in the lasers of only 100 watts and 10 kilowatts, respectively. Such power dissipations would present no problems if gas lasers were used (*27*).

The major difference between the two-step process just described and the all-infrared process is the use in the latter of an infrared laser for the second step instead of an ultraviolet laser. There are several possibilities being explored for this stage, including the use of the same laser for both isotopically selective excitation and dissociation. However, there are virtually no available data on which to base a yield estimate for this process.

We are forced to the conclusion that the molecular process may be inherently capable of considerably higher production rates than the atomic process for a given interaction volume. There is nothing in the basic physics of the molecular process which will guarantee that a laser enrichment facility capable of producing substantial amounts of high-enriched uranium in short periods of time will be either very large or outrageously expensive. However, there do remain some problems with the chemistry of the process, and I will consider these in the next section.

Obstacles to Practical Laser Enrichment

In the last two sections I have described the basic physics of laser isotope separation in atomic and molecular uranium. In each case I have tried to single out the interaction which places an upper bound on the selectivity obtainable in the process. In the atomic case it seems clear that this process is the charge exchange between ionized ^{235}U atoms and neutral ^{238}U atoms. In the molecular case we have taken it to be resonant vibrational energy exchange, although there is some reason to suspect that recombination of dissociated molecules may ultimately impose a more severe limitation. It is not possible to estimate this, however, in the absence of relevant data. In each case the limiting interaction determines a maximum density for the feed material, and this density, along with the beam energy densities and pulse rates of the lasers, determines the rate at which an enriched product can be produced.

I now want to examine each of the processes and try to get a feeling for the technical difficulties that must be overcome before macroscopic quantities of enriched uranium can be produced. For most commercial processes it is a long way from the basic physics to a final product, and this time lag would certainly seem to hold true for laser enrichment. Several years of effort have already been expended by substantial numbers of scientists in several countries, and there is not even so much as a model facility operating anywhere, unless it is a very well-kept secret. It seems fair to assume, therefore, that the development of a laser enrichment technology is a difficult problem requiring a major research and development effort by a first-rate technical establishment. The implications of this requirement for the proliferation question are important and will be dealt with in the next section.

Atomic methods. The corrosiveness of uranium vapor is certainly one of the most serious obstacles to contend with in the atomic process (*10*). This problem, like the separation chemistry for UF_6, is not discussed in any detail in the literature on laser enrichment, and it seems fair to assume that one of the primary motivations of Jersey Nuclear–Avco for building an experimental facility is to test various means of controlling the reactivity of uranium vapor. If it should prove necessary to shut down a laser enrichment plant at frequent intervals to clean or replace the atomic beam apparatus (which will be very large and awkward to handle), then the economics of such a plant are made considerably less promising.

Another serious difficulty associated with the use of high-temperature uranium vapor is the presence of thermally excited and even ionized atoms in the beam. The uranium atom possesses a very inconveniently located excited state which is only 0.077 electron volt above the ground state. This energy is easily supplied to atoms colliding at 2500°K, and in thermal equilibrium one expects to find only 45 percent of the uranium atoms in the ground state and 27 percent in the first excited state. Since these two groups account for only 72 percent of the atoms, the other 28 percent are spread out among even higher excited states.

This problem is analogous to the "hot bands" problem in the molecular process, but there is no analogous solution in the atomic case since there is no way to expand the already rarified vapor to cool it. Thus one must either be content with exciting fewer than half of the ^{235}U atoms in the beam or one must use two ultraviolet lasers (*8*) which differ in frequency by 620 reciprocal centimeters in order to excite 72 percent of the ^{235}U. Since this is the initial excitation step, both of these lasers must be of the very narrow-band, isotopically selective type, and, since the densities of the two types of atoms differ by a factor of 2, the interaction lengths in the vapor of the two beams will be very different unless there is a fortuitous relationship between the two excitation cross sections. This difference in beam lengths could lead to a further loss of efficiency.

Then there is the problem of thermally ionized ^{238}U atoms. The presence of even a small concentration of ^{238}U ions in the beam will seriously degrade selectivity, since the $^{235}U/^{238}U$ ratio is already very small. For example, if only 0.1 percent of the ^{238}U is ionized (*28*), this will put an absolute upper limit on the $^{235}U/^{238}U$ product ratio of 5 even if we assume that 70 percent of the ^{235}U can be ionized. Therefore, it is essential that the number of thermal ions in the atomic beam be kept very small. The ionization problem is even more severe when electron beam evaporation is used instead of high temperatures.

Another potentially tricky problem arises if the intermediate excitation state is saturated as described in the section on laser enrichment with atoms. In this situation the atomic vapor column is just on the verge of becoming a laser itself. The density, energy levels, cross sections, and laser powers must all be chosen carefully to prevent the vapor column from becoming a laser, since stimulated emission from the excited state will simply undo the work done by the external lasers.

Moreover, if the atomic ribbon is actually to be of the order of hundreds of meters long or if some multiple-pass geometry is to be used, there is a significant time delay before a laser pulse emitted at one end of the interaction volume can reach the other. Light takes 3×10^{-7} second to travel 100 meters, but pulse durations are expected to be of the order of 10^{-7} second [see (*11*), p. 140]. So a particular laser pulse will occupy only about one-third of the length of the column at any instant of time. This could lead to problems of timing with the second excitation pulse and the ionizing and collecting processes.

The power required from the lasers in the atomic process is not as great as for the molecular process, but the pulse repetition rate must be higher to obtain reasonable production rates. Both of these requirements follow from the fact that the atomic vapor is of the order of 10^3 times more rarified than the molecular vapor (see Table 1). This fact also ensures that an enrichment facility that uses the atomic method will have to be much larger than one that uses UF_6. The combined demands for energy density, repetition rate, tuning precision, and stability and reliability of the lasers are quite severe. No currently available lasers can meet these demands, and, according to Rhodes, ". . . the creation of the appropriate high power lasers will be the pacing item for developing a commercial process. An integral involvement with the university and industrial laser complex is paramount to the success of this program" (*29*, p. 14).

Molecular methods. There have been no publicly announced experiments in which uranium has been enriched by molecular methods, not even in milligram amounts. The reason is that no laser has yet been devised with a wavelength near 628 reciprocal centimeters and sufficient power to dissociate $^{235}UF_6$ molecules in macroscopic quantities. Selective excitation has been observed, but only in spectroscopy experiments in which very low-power semiconductor diode lasers were used (*19*).

It would be difficult to argue that the invention of a tunable infrared laser with a wavelength in this region is unlikely. It is always possible that a determined search will turn up a new molecular transition that can be made to lase near the proper frequency. There are also many schemes under study for downshifting existing laser frequencies, in particular the 10-micrometer CO_2 manifold in which high powers and high efficiencies have already been attained (*30*). The use of either nonlinear optics or stimulated Raman emission has been suggested (*31*), and, once a frequency close to the desired frequency is obtained, there are a number of other methods that can be used to achieve the fine tuning necessary to make the laser isotopically selective. The demands on the secondary laser are severe, especially in terms of pulse energy, repetition rate, and efficiency.

An indication of the current state of the infrared laser art with regard to enrichment technology can be gathered from the following statement made by Rockwood in a paper contributed to the Laser Spectroscopy Conference in Loen, Norway, in May 1976 (*32*). Rockwood believes that "this represents a new era for laser researchers in that they are now being asked to invent a laser to order with respect to wavelength, energy and efficiency" (*32*, p. 7). He also says that "It will be interesting to observe whether our knowledge of lasers has really progressed to the point that these requests can be met in a timely manner" (*32*, p. 7). It is certainly fair to infer from these statements that the development of suitable lasers is still highly problematical and that without such lasers the technology will probably never come to fruition.

If we grant the existence of the necessary lasers, then the major obstacle to enrichment in UF_6 becomes the separation of the dissociated product from the depleted tails. Unless this process is quite efficient, the high selectivity achievable by the lasers will be dissipated in recombination of the dissociated products or by exchange interactions. Indeed, one can visualize a molecular interaction completely analogous to charge exchange in the atomic process. In this mechanism a $^{235}UF_5$ molecule would interact with a $^{238}UF_6$ molecule to produce $^{235}UF_6$ and $^{238}UF_5$, the latter, of course, present along with the $^{235}UF_5$ in the product. Just as in the atomic case, this reaction must be kept to a very low rate if any respectable selectivity is to be maintained. One can speculate that this goal can be achieved with the use of an appropriate buffer or scavenger gas, or both, but the strong suspicion remains that this problem or one very much like it has not yet been solved and may turn out to limit the selectivities and yields which can be achieved in practice to values considerably less than the data in Table 1 would indicate.

This concludes my discussion of the major obstacles to laser enrichment of uranium. It is certainly not a complete list of obstacles, and it may be that from my position outside of the active research field I have overrated some problems. But it seems equally likely that there are serious problems I have not even thought about and others which have yet to arise. It would be foolish to predict that the problems will be insoluble, especially if one grants that a powerful economic incentive exists to solve them. It does seem reasonable to assume, however, that, if the difficulties were easily overcome, laser enrichment would by now be a fact of life. It must also be kept in mind that, even if laser enrichment should turn out to be technically feasible and economically profitable for low enrichments on a large scale, it does not follow that the technique will be either feasible or practical for high enrichments on a small scale. These high enrichments are the real issue in the proliferation question. We must now consider this question in the light of what I have said about laser enrichment.

Consequences for Nuclear Proliferation

It is possible to imagine two important motivating forces behind the development of laser enrichment, one economic and the other military-strategic. Laser enrichment may make reactor fuel cheaper and more plentiful and it may also provide a large market for sophisticated, high-powered lasers. On the other hand, it may offer countries that would otherwise consider nuclear weapons to be out of their reach an easy entrance into the "nuclear club." I will consider both of these motivations but will place a greater emphasis on the second one, since this is the major objective of my argument.

The impetus behind the development of laser techniques in the major nuclear powers is overwhelmingly economic. It derives from the presumed need for expanded uranium enrichment capacity in a growing nuclear economy and the hope that smaller, less capital- and energy-intensive laser enrichment facilities will provide more planning flexibility and reduce the financial risks involved in increasing enrichment capacity. Proponents of laser enrichment begin many of their papers and lectures with references to the projected growth in demand for enriched uranium over the next 30 years. If such projections are valid, there is a clear incentive for finding an enrichment technology which requires lower capital investment and promises substantially reduced energy demands.

But are these projections valid? Many people are beginning to doubt it very seriously. It is clear that the optimistic predictions for the growth of nuclear power generation which prevailed two or more years ago must now be revised downward, and no one is sure just how large these revisions will be. There is ample evidence of increasing public disenchantment with nuclear power in the United States and in several Western European countries, and the present and projected economic difficulties associated with the attempts of electric utilities to convert to nuclear generation are too well known to need discussion here.

In an article entitled "Laser isotope separation overview" (*33*) Boyer was optimistic about the future evolution of the technology because "large economic incentives exist to drive such a development . . ." (*33*, p. 9). It will be interesting to see whether this statement remains true over the next several years during which a lot of money will have to be spent on research and development in order to bring this technology into commercial operation. It will also be interesting to see how industry's attitudes will be affected if the enrichment business is not turned over to private enterprise. This proposal is currently under heavy fire and may be withdrawn by the Carter Administration.

The other set of motivations, military and strategic, relates directly to the problem of the horizontal proliferation of nuclear weapons. In order to assess the threat which laser enrichment poses for nuclear weapons proliferation, we must ask whether this technology significantly reduces the difficulties faced by a non-nuclear weapon state or organization which decides it wants to acquire some bombs.

For the purposes of this argument I will assume that natural uranium is and will continue to be readily accessible to any state that would like to buy it or mine it. The 1968 Treaty on the Non-Proliferation of Nuclear Weapons places no restrictions on the production or sale of natural uranium, and such restrictions are highly unlikely in the foreseeable future. The technologies for turning uranium ore into pure uranium metal or UF_6 are quite straightforward and certainly accessible to anyone, although UF_6 does require careful handling. The amount of natural uranium needed to produce 20 kilograms of high-enriched ^{235}U is of the order of 2.5 metric tons if one assumes that there is no waste, and so in practice it will take several tons of natural uranium to produce each bomb.

Another alternative is to use already partially enriched uranium which has been diverted from its intended use as reactor fuel. Any country that possesses one or more nuclear reactors requiring enriched uranium could use this option if it chose to. But such a country would also have the option of burning the fuel in a reactor and then reprocessing the spent fuel to obtain plutonium for its weapons program.

The countries or groups we have to consider in answering the questions about proliferation divide quite naturally into two groups: those with one or more nuclear reactors under their control, and those with no reactors and therefore no need for enriched uranium or means to produce plutonium. For the former group we must consider the laser enrichment option to be in competition with the option of producing plutonium by spent fuel diversion and reprocessing. For the latter group we must consider the development of a laser enrichment facility in competition with the acquisition or construction of a reactor, or the option of the theft or purchase (presumably on a black market) of weapons-grade material. Of course, these last options are also available to countries with reactors, and under certain conditions might have advantages over the construction of a reprocessing plant.

The costs and risks associated with any of the above options will obviously depend very heavily on the condition of the worldwide nuclear economy and on the system of safeguards which exists to prevent proliferation. One does not have to study the current situation very deeply to develop a sense of profound discouragement with the chaotic state of the world's nuclear economy and with the hypocritical, self-serving, and counterproductive attitudes and actions of the major nuclear powers. Many investigators (*34*) have called attention to the inadequacies in the safeguard systems designed to prevent nuclear theft or diversion, and others (*35*) have become increasingly alarmed at the substantial political pressures which seem to be leading inexorably toward further proliferation of nuclear weapons.

If my assessment is to be realistic, it must be made within this present political and technological context. Most experts on the proliferation question agree that there is no current or seriously contemplated antiproliferation mechanism which could prevent any country that seriously wanted nuclear weapons from obtaining them. According to Epstein [see (*35*), p. 40], "It has been estimated that a [nuclear fuel reprocessing] plant capable of producing 15 to 20 kilograms of plutonium 239 a year (enough for 2 or 3 explosive devices) could be built in a year or two by any reasonably advanced country at a cost of 1 to 3 million dollars." According to Taylor, this figure is "if anything a bit high" (*36*). In a study carried out for the Congressional Research Service of the Library of Congress, Lamarsh (*37*, p. 19) has concluded that for countries without reactors

> many small and/or developing nations can probably build a nuclear reactor capable of producing significant amounts of plutonium for a weapons program. Such a reactor would circumvent the necessity of diverting plutonium from nuclear power plants.

Lamarsh reached a similar conclusion regarding a small reprocessing plant to separate the plutonium produced by the reactor (*38*). His estimate of the cost of the combined reactor-reprocessing facility is \$20 million to \$40 million, but he emphasized that this estimate is based on U.S. prices and labor costs and that significantly lower costs might be achieved in other countries. Finally, Lamarsh estimated the time necessary from the point of decision to build such a plant to the point at which bombs can be fabricated as about 5 years (*37*, p. 18). No highly specialized technical personnel are required either for the construction or for the operation of the plant.

With these considerations in mind, what can be said about the proliferation potential of laser enrichment? The most obvious answer is that it is still too early to say much of anything. The technology does not yet exist, and the optimistic projections of many of its promotors must be substantially discounted. Such expressions of optimism are to be expected from people who are professionally, financially, or emotionally involved with the process and who are anxious to gain support for their research or to justify substantial research and development investments to their stockholders. On the other hand, my analysis has shown that there are no obvious natural barriers to the eventual creation of small-scale enrichment facilities capable of producing several critical masses of high-enriched ^{235}U per year at a price which can be imagined to be competitive with the \$20 million to \$40 million estimated by Lamarsh for a plutonium facility (*38*).

A great deal depends on the answers to the following four questions:

1) Will the world nuclear economy continue to grow, spreading nuclear reactors moderated by light water to more and more countries and stimulating an increasing demand for small-scale enrichment facilities?

2) Will the strategic and political incentives which now appear to encourage some nonnuclear countries to acquire nuclear weapons continue to exist in the future, and will the problem of creating an effective worldwide system of security guarantees and nuclear safeguards continue to defy solution as it has in the past?

3) Will the lasers and materials-handling techniques associated with laser enrichment be technically simple enough and in sufficient demand so that keeping them secret is impossible?

4) Will it be possible to modify laser enrichment plants designed for producing low-enriched reactor fuel at reasonable cost and with available expertise to produce high-enriched nuclear explosives?

Obviously if the answers to all four of these questions are "yes," then laser enrichment will create a new and potentially dangerous threat of proliferation of nuclear weapons. But at the same time an affirmative answer to questions 1 and 2 guarantees that the proliferation threat will remain alive and vigorous whether laser enrichment is developed or not. In this case laser enrichment must be thought of as just one more hole in an already leaky sieve.

If the answer to question 3 turns out to be negative, one can assume that the laser enrichment technology will be achieved only by those countries technologically and economically advanced enough to possess a "university-industrial laser complex." However, these countries already have several other options for making weapons should they choose to do so, and the proliferation issue with these advanced countries is entirely one of incentives rather than capabilities or economic costs.

Question 4 raises an issue that is also of concern to many in the arms control field. If laser enrichment facilities for making reactor fuel become economically attractive to countries with only a few reactors, then the acquisition of these facilities demands no commitment or even desire to make nuclear weapons. However, if the facility could be easily modified to produce weapons-grade material, then the step that must be taken to begin making weapons in response to some military provocation or shift in political leadership would be considerably easier than it is at present. In this way laser enrichment could contribute to lowering the barriers to proliferation in a manner similar to the diffusion of reprocessing technology.

It is clear from this analysis that the potential development of laser enrichment technologies must be taken seriously in any strategy to stop nuclear weapons proliferation. At the same time it must also be obvious that the possibility of this new technique in no way lessens the need to establish firm controls over fuel-reprocessing technologies and plutonium traffic. The existence of a full-scale worldwide plutonium economy would make the laser enrichment threat pale by comparison, and the highest priority is still, and will almost certainly remain, a system of safeguards which will prevent the diversion of plutonium and the widespread acquisition of fuel-reprocessing technology. This idea can be asserted even more strongly in the case of terrorist groups or criminals attempting to acquire weapons. It seems highly unlikely to me that a laser enrichment facility would ever reach the level of simplicity and cost-effectiveness to make it attractive to such groups, and that the option of stealing or buying plutonium or weapons-grade uranium on a black market is still the one against which safeguards must be designed. Many observers believe that the existence of such a black market will be an inevitable feature of a world nuclear economy. Some fear it may exist already [see (*35*), p. 260].

Policy Issues

There are four major policy issues involved in the laser enrichment question. They relate (i) to the overall policy of the United States and other countries toward nonproliferation of nuclear weapons, (ii) to the possible commercial takeover of the enrichment industry in the United States, (iii) to the research priorities in government-controlled laboratories, and (iv) to the question of secrecy and how it can be reconciled with the need for a public assessment of this new technology.

Laser enrichment must be considered within the overall context of a worldwide policy of control of nuclear materials and processes. This policy includes enrichment, reprocessing, and waste management; it probably will eventually have to include mining and milling operations for natural uranium as well. The possible advent of laser enrichment seems to me to create no important changes in the agenda for nuclear policy-makers. The major problem facing the world is still the control of plutonium. If we can imagine a political climate within which the plutonium problem can be solved, it does not stretch the imagination much farther to imagine a world in which laser enrichment facilities would be under the same kinds of controls. The laser enrichment problem is not so different from the fuel-reprocessing problem that they cannot be dealt with in quite similar ways.

A general discussion of the problem of proliferation is beyond the scope of this article. It will suffice if I express my own opinion that the current efforts by the nuclear powers to prevent any more countries from obtaining these weapons are based on a fundamentally unjust and ultimately unworkable principle of permanent asymmetry of power. The nuclear powers are demanding total acquiescence of the nonnuclear countries and have shown themselves unwilling to make even token concessions to the legitimate security and economic concerns of the nonnuclear nations. Because of these attitudes, the Non-Proliferation Treaty has become almost a dead letter, and, as Epstein (*35*) and others have shown, the political pressures for proliferation are increasing rapidly. Nothing short of a universal commitment to a system of international guarantees against any nuclear attack on nonnuclear nations would be able to relax this pressure. One does not meet many people who are optimistic about this question.

The second major policy issue concerns the attempts by the Nixon and Ford administrations to turn the enrichment business over to private industry. Strong arguments against this plan had been voiced even before the prospect of laser enrichment, but this new development would seem to call even further into question the wisdom of this policy. If one feels that a serious proliferation threat would result from the development of a relatively inexpensive and small-scale enrichment technology, then it would seem illogical to create a strong economic incentive for just such a development.

The third policy issue concerns the motivations for the obviously intense research programs being carried out at the national laboratories at Los Alamos and Livermore. Economic considerations may play some part here, since, if the government is to expand its enrichment capacity, there are obvious benefits in finding a less capital- and energy-intensive way of doing it. But one suspects that other considerations are at least as important in the case of government-sponsored research. I believe that two other important motivations are the scientific "sex appeal" of the process and the knowledge that the Soviet Union and Israel, and possibly other countries as well, are heavily involved in research and development of laser enrichment.

The first motivation can be a powerful one. It would be a mistake to underestimate the great desire of scientists to achieve something "technically sweet" and then, as Robert Oppenheimer once said about the hydrogen bomb, "worry about the consequences later" (*39*, p. 251). There is certainly no argument about the technical sweetness of laser enrichment compared to, say, gaseous diffusion.

There is evidently some element of competitiveness vis-à-vis the Soviet Union and Israel (not to mention that between Livermore and Los Alamos). But probably more important than the "feather-in-our-cap" motivation is the desire to head off any technological surprises. If the United States is to have a major influence on the evolution and control of laser enrichment technology, then it would seem to be important that we be as knowledgeable about it as anyone else. There is much to be said for this position, and it remains difficult to argue in favor of simply turning one's back on a new technological possibility which promises significant conservation of energy, capital, and resources, even in view of the many bitter experiences we have had in the past.

One very positive result which might emerge from a continued effort in research is a way to design laser enrichment plants to make it impossible or extremely impractical to convert them from producers of low-enriched reactor fuel to producers of high-enriched weapons material. This restriction would make it far easier to justify their ultimate development and dissemination.

The final policy question concerns the need for a public discussion of the desirability and potential impact of laser enrichment and the ways in which the current climate of secrecy conflicts with that need. At the present time, none of the scientists or administrators who are actually involved in the research and development effort are able to talk about it except in the most bland generalities.

What can we hope to gain by preventing public access to the results of the research now being carried on? Probably the best that the "classifiers" can hope for is to buy some extra time in which to think about the problem of what to do with the technology. If the process turns out to be easy to develop, then one must assume that others will be able to develop it whether they are given the information or not. If, on the other hand, there are devices or techniques that are essential to obtaining high enrichments and that are sufficiently esoteric to make their discovery by others very difficult, then there may be important aspects of the research that should be kept secret. Unfortunately, one cannot decide this question unless one knows what the secrets are, and so there is no easy answer to this question. One can only urge those with the authority to do so to release to the public as much information as possible, so that an informed discussion of this potentially useful but potentially dangerous new technology can begin.

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20. Some of the ideas mentioned in this paragraph were discussed by D. Cox of the Exxon Research Laboratories in a colloquium delivered at the Princeton University Engineering School, Princeton, N.J., on 12 October 1976.
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22. R. V. Ambartsumyan, Yu. A. Gorokhov, V. S. Letokhov, G. N. Makarov, *JETP Lett.* **21**, 171 (1975); R. V. Ambartsumyan, Yu. A. Gorokhov, V. S. Letokhov, A. A. Puretskii, *ibid.* **22**, 177 (1975); J. L. Lyman, R. J. Jensen, J. Rink, C. P. Robinson, S. D. Rockwood, *Appl. Phys. Lett.* **27**, 87 (1976).
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24. This number has been derived from an absorption coefficient of 0.2 cm^{-1} torr^{-1} for ν_3 radiation in UF_6 quoted by Cox [see (*20*)].
25. J. H. Birely, D. C. Cartwright, J. G. Marinuzzi, *Proc. Soc. Photo-Opt. Instrum. Eng.* **76**, 124 (1976), tables 3 and 4.
26. The assumptions and result for this calculation are summarized in Table 1.
27. Birely *et al.* (*25*) propose a 5000-hertz pulse rate for the ultimate production lasers. This specification would demand very large energy dissipation capability in the ultraviolet or high-power infrared lasers. This capability can presumably be achieved, but such lasers would be very sophisticated and expensive. A 100-hertz pulse rate is easier to achieve and still allows for the production of ^{235}U at reasonable rates if the other parts of the process work as hoped.
28. This was the proportion of thermally ionized atoms in the experiment described by Snaveley *et al.* (*8*).
29. G. W. Rhodes, in *Laser Photochemistry, Tunable Lasers, and Other Topics*, S. F. Jacobs, M. Sargent III, M. O. Scully, C. J. Walker, Eds. (Addison-Wesley, Reading, Mass., 1976), pp. 11–16.
30. For the most recent suggestion, see R. L. Byer, *IEEE J. Quantum Electron.* **QE-12**, 732 (1976).
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32. S. D. Rockwood, "Uranium isotope separation and its demand on laser development" (report LA-UR-76-1169, Los Alamos Laboratories, Los Alamos, N.M., 1976).
33. K. Boyer, in *Laser Photochemistry, Tunable Lasers, and Other Topics*, S. F. Jacobs, M. Sargent III, M. O. Scully, C. T. Walker, Eds. (Addison-Wesley, Reading, Mass., 1976), pp. 1–9.
34. For example, see M. Willrich and T. B. Taylor, *Nuclear Theft: Risks and Safeguards* (Ballinger, Cambridge, Mass., 1974).
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37. J. R. Lamarsh, "On the construction of plutonium-producing reactors by small and/or developing nations" (report prepared for the Congressional Research Service of the Library of Congress, Library of Congress, Washington, D.C., 30 April 1976).
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40. I appreciate several very helpful discussions with R. Miles, F. von Hippel, and T. Taylor. I also thank J. Lyman, C. D. Cantrell, C. B. Moore, R. Garwin, A. Lovings, and H. Federow for useful comments on an earlier draft. I thank I. Glassman for extending to me the hospitality of the Princeton Center for Environmental Studies. Supported under a National Science Foundation Faculty Fellowship for Science Applied to Social Problems.

Cardiac Pacemaking: An Obligatory Role of Catecholamines?

A possible mechanism underlying spontaneous pacemaking can be deduced from several recent clues.

Gerald H. Pollack

In the most recent comprehensive review of sinus node function, Brooks and Lu (*1*) concluded that the underlying mechanism of pacemaker action in the heart remained a mystery. Since then, several clues have been found which make it appropriate to reexamine the question of pacemaking in a new light. It appears that a solution to the mystery may lie in a heretofore unrecognized role of catecholamines.

It is well known that catecholamines increase the speed of spontaneous depolarization in pacemaker cells, thereby elevating the heart rate (*2*). It now appears that this familiar postsynaptic role of catecholamines may be complemented by an equally important presynaptic role. In this article I consider the evidence that pacemaker cells store and secrete catecholamines, and that they are unable to pace when deprived of the action of both pre- and postsynaptic pools of catecholamines.

Do Pacemaker Cells Store Catecholamines?

Early histological studies of the heart demonstrated that the region of the sinus node was densely innervated (*3*). Thus, when the paraformaldehyde fluorescence technique was applied to evaluate the regional distribution of catecholamines in the heart (*4*) it came as no surprise that the sinus node was richly endowed with catecholamines. However, not all the catecholamines are stored in nerve terminals. In dog hearts that had been denervated both surgically and chemically (with 6-hydroxydopamine), the sinus node was found to have retained about half the epinephrine present in nondenervated controls (*5*). The authors of this study concluded that the storage of catecholamines was in part extraneural, possibly in specialized catecholamine-storing cells which were analogs of the chromaffin cells of the adrenal medulla.

Extraneural storage of catecholamines is also found in the embryonic heart. Although embryonic heart cells and pace-

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