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Soviet Research on Laser Isotope Separation for Uranium Enrichment [redacted]

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An Intelligence Assessment

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Soviet Research on Laser Isotope Separation for Uranium Enrichment [redacted]

An Intelligence Assessment

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Top Secret
SW 85-10101CX
[redacted]
September 1985

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Soviet Research on Laser Isotope Separation for Uranium Enrichment [redacted]

Key Judgments

Information available as of 15 May 1985 was used in this report.

Because of well-publicized long-range Soviet/CEMA plans calling for increased nuclear power production, we believe that at some time during the 1990s the Soviet Union will need additional capacity for producing enriched uranium. By virtue of their relatively low power consumption, the two enrichment (isotope separation) technologies most likely to be considered for this expansion are advanced gas centrifuges and laser isotope separation (LIS). We believe, however, that Soviet LIS technology is only in an early stage of development and could provide no additional enrichment capacity during the 1990s. We judge that the Soviets will continue to investigate LIS because of its potential for recovering uranium-235 (U-235) from existing enrichment wastes. ([redacted]

Information from [redacted] open literature establishes that the Soviets have been researching laser isotope separation techniques since the early 1970s. Although this research has apparently been directed toward the development of a process for enriching uranium, the Soviets have actually done very little of their work with uranium. The United States has done extensive enrichment research using uranium and has undertaken experiments with methods of collecting U-235 [redacted]

[redacted]

Contents

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Soviet Research on Laser Isotope Separation for Uranium Enrichment [redacted]

Background

Natural uranium contains only 0.7 percent of the fissile isotope U-235. Nuclear power reactors require low-enriched uranium (LEU), which typically contains several percent of U-235; nuclear weapons require highly enriched uranium (HEU), which is about 90 percent U-235. The uranium isotope separation, or enrichment, techniques most commonly used to produce LEU and HEU are gaseous diffusion and, more recently, gas centrifuge. This paper discusses a new enrichment technique, or group of techniques: laser isotope separation, which is in the developmental stage but offers some advantages over uranium enrichment techniques already developed. (See appendix for technical details of LIS techniques.) ([redacted]

[redacted] because of their expanding nuclear power program, at some time during the 1990s the Soviets will need additional LEU capacity [redacted] in the form of either upgraded or new plants. The technologies most likely to be considered for these plants are LIS and advanced gas centrifuges. Although Soviet discussions about which technology to use will undoubtedly revolve around the technical status of each, the final decision will probably be strongly influenced by considerations of economics, bureaucratic infighting, and installed production capacities for equipment. If a long-range viewpoint is taken, another important consideration would be the capability of LIS to recover U-235 from existing wastes. [redacted]

[redacted]

Development

Pre-1976 Classified Program

While he was a researcher at the Lebedev Institute during the late 1960s, V. S. Letokhov developed the basic ideas for the principal LIS techniques: atomic vapor laser isotope separation (AVLIS) and molecular laser isotope separation (MLIS). After becoming deputy director of the newly established Institute of Spectroscopy (IOS) in 1970, Letokhov became an active advocate for laser spectroscopic research (the investigation of the energy levels of atoms/molecules by laser excitation). We believe that, in order to obtain support from the ministries, he emphasized the applicability of laser spectroscopy to LIS and, in particular, to uranium enrichment. ([redacted]

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Development of Molecular Laser Isotope Separation [redacted]
The Soviets have done extensive research on the laser spectroscopy and laser isotope separation of molecules containing elements significantly lighter than uranium. The prevalence of MLIS in the Soviet research program is probably due to the prominence of Letokhov. Soon after developing the ideas for MLIS and AVLIS in the late 1960s, Letokhov decided that MLIS appeared to be the easier of the two processes. He continued to actively promote MLIS throughout the 1970s. [redacted]

[redacted]

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[redacted]

[redacted]

These groups have done only limited work with molecules cooled below room temperature. (US scientists believe that UF_6 molecules must be supercooled to very low temperatures before isotopic separation is feasible. See the appendix for more details.) [redacted]

The goal of the Soviet research on MLIS-related topics was to understand the physical and chemical processes involved. As with similar work in the United States, this effort was only partially successful. Although the Soviets realized that these empirical results could not be directly applied to the more difficult UF_6 situation, they apparently were unduly influenced by them. [redacted]

During the late 1970s, the groups under Letokhov and Karlov did a few experiments on room-temperature UF_6 molecules. At that time a group under Kikoin at the IAE also became involved in uranium MLIS research. Although much of the research of this latter group is relevant to the development of a supercooled UF_6 MLIS process, the group has done only a few experiments with supercooled UF_6 molecules. Most of its research on supercooled gases has been done with SF_6 molecules. In addition, it has done research on various schemes for the laser excitation of room-temperature UF_6 molecules. ([redacted]

The Soviet uranium MLIS programs appear to be of an academic or basic physics nature. Although the Soviets seem to be progressing toward a technique using supercooled UF_6, they apparently are not yet committed to this technique nor have they defined the appropriate laser excitation scheme to use. Thus, we believe that the Soviets are still in the laser spectroscopy phase of their uranium MLIS program and have done very little work on developing the equipment for an experimental verification phase. [redacted]

Once the Soviets decide to develop an MLIS technique, it is likely that Kikoin's group will be in charge of such development. This group has been responsible for investigating new uranium enrichment techniques for several decades and has ministerial and industrial connections. When this group became involved in uranium MLIS, it lacked much of the expertise necessary for the needed research. A partial remedy for this situation was brought about by collaboration with Karlov's MLIS scientists and with a laser-diode group under L. N. Kurbatov. Although Kurbatov headed a group at the Lebedev Institute during the 1970s, his principal position since 1960 has been deputy director for science of the Scientific Research Institute of Applied Physics in Moscow. This institute is subordinate to the Ministry of Defense Industry and has connections to the Lebedev Institute through the VPK. ([redacted]

Development of Atomic Vapor Laser Isotope Separation [redacted]

The Soviets have placed little emphasis on AVLIS-related topics. Although scientists at the IOS have done a few experiments on the AVLIS of some rare earth elements, most of their research with atoms and atomic vapors has been related to the detection of single atoms for various non-LIS applications. ([redacted]

[redacted]

[redacted]

Most of the Soviet research on AVLIS has been done by a group under Karlov. During the 1976-78 time period, this group conducted a systematic investigation of the AVLIS of most rare earth elements. During the early 1980s, it continued to consider variations on the basic scheme used in these earlier experiments. [redacted]

Prospects

For the last 10 years, the Soviets have been actively pursuing LIS research. Although only a small amount of this research has been with uranium, we believe that the primary goal of this research is to develop the basis for a uranium LIS program. [redacted]

The Soviets have favored MLIS over AVLIS since the beginning of the 1970s and have invested most of their LIS research effort in MLIS topics. Almost all of their efforts on uranium MLIS have been done at room temperature and with CF_4 lasers that cannot strongly excite the best molecular energy levels. [redacted] The United States has concentrated its LIS research on uranium enrichment by supercooled MLIS and AVLIS, with the present emphasis being on AVLIS. In addition, the United States has built complete prototype systems and performed collection experiments. [redacted]

Once the Soviets complete the laser spectroscopy phase of their LIS programs, decide to develop AVLIS or MLIS, and determine the detailed characteristics of the process, it will, we believe, take them [redacted] years to complete their program through the demonstration phase. (See the appendix for details on the complexity of these phases and estimated times for completion.) If the Soviets should have a pressing need for additional capacity to produce LEU when this phase is complete, they could use the test setup to produce reasonable amounts of LEU. [redacted]

From past Soviet practice, however, we believe that the first significant Soviet production of LEU by LIS will be done in a plant dedicated to that purpose. [redacted] How much longer it is before an LIS plant actually comes on stream will depend on such factors as:

- The availability of other technologies such as the gas centrifuge.
- The political clout of the LIS hierarchy.
- The perceived economics of the LIS process.
- Changes in the demand for LEU.
- The supply of high-grade uranium ore.
- Technical difficulties encountered. [redacted]

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[redacted]

Appendix

Laser Isotope Separation Techniques

Worldwide predictions during the mid-1970s indicated that civilian nuclear power would grow at a rapid rate. (These predictions were very optimistic.) Suppliers of low-enriched uranium, such as the United States and the Soviet Union, it was believed, would need to build several new large uranium enrichment plants before the year 2000. Accordingly, these countries and others began investigating improved enrichment techniques such as advanced gas centrifuges and laser isotope separation. This appendix discusses the potential advantages, the details, and the developmental phases of an LIS process. [redacted]

An LIS module (a separation device through which the uranium flows once) has a potentially large enrichment factor: that is, only a few LIS modules would be needed to produce the same enrichment that is obtained by using thousands of gaseous diffusion modules or hundreds of gas centrifuges. In addition, LIS is much less power intensive than gaseous diffusion and somewhat less so than gas centrifuges. The combination of these factors makes LIS much cheaper than gaseous diffusion and also potentially cheaper than gas centrifuges. [redacted]

Another advantage of an LIS plant is that, like a gas centrifuge plant, it can be built in modular form. That is, it is possible to construct a moderate-capacity plant that can be added to as additional capacity is required. Gaseous diffusion plants do not have this flexibility. [redacted]

Gaseous diffusion and gas centrifuge plants cannot economically separate more than about two-thirds of the desired U-235 from the natural uranium feed material. An LIS plant can economically separate out more of the U-235; in addition, unlike the other processes, it can be used to recover much of the U-235 present in the wastes, or tails, that have been accumulated over the decades of gaseous diffusion plant operation. [redacted]

Molecular laser isotope separation (MLIS) and atomic vapor laser isotope separation (AVLIS) are the principal LIS techniques being researched. They both depend on being able to precisely tune a laser to an atomic or molecular energy level. The two techniques differ in the types of feed material, lasers, and collection methods used. The equipment used also varies with the element whose isotopes are being separated. [redacted]

The uranium MLIS technique involves the laser excitation and dissociation of molecules containing U-235 atoms. Uranium hexafluoride (UF_6) is the gas most generally used in a uranium MLIS process. The UF_6 molecules are selectively excited using an infrared (IR) laser and dissociated using an IR or an ultraviolet laser to break a U-F bond (figure 1). Although the UF_6 molecule can be made to vibrate in six modes, only two of these are sensitive to the mass of the uranium atom and produce an isotope shift (a difference in the energy spectra of molecules containing U-235 and U-238 atoms). The sensitive mode that is the more efficient of the two for breaking U-F bonds has a characteristic energy corresponding to a laser wavelength of about 16 micrometers. Unfortunately, there are no lasers having a natural wavelength of the appropriate value; the CF_4 laser has a wavelength in the vicinity of 16 micrometers but is inefficient for exciting the appropriate UF_6 mode. Although there is a combination of vibrational modes in the 8.6-micrometer wavelength region that can be excited using a CO_2 laser, the probability of excitation is small. [redacted]

The use of room-temperature UF_6 introduces technical difficulties because of thermal excitation of low-lying vibrational levels. US scientists believe that the effects of this nonselective thermal excitation are severe enough to make a room-temperature process

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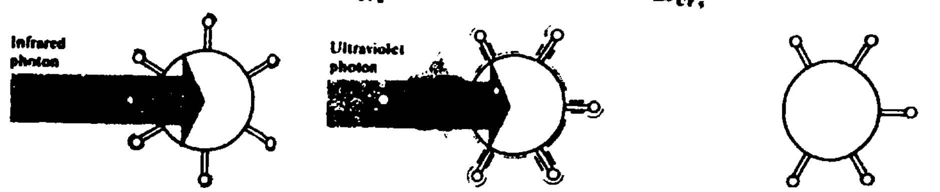
Figure 1
Molecular Laser Isotope Separation (MLIS) Process



An infrared photon excites (sets vibrating) the $^{235}UF_6$ gas molecule.

An ultraviolet photon is absorbed by the excited $^{235}UF_6$ molecule, causing it to lose one of its fluorine atoms.

The new molecule, $^{235}UF_5$, is a powder, which can be easily removed from the gas.

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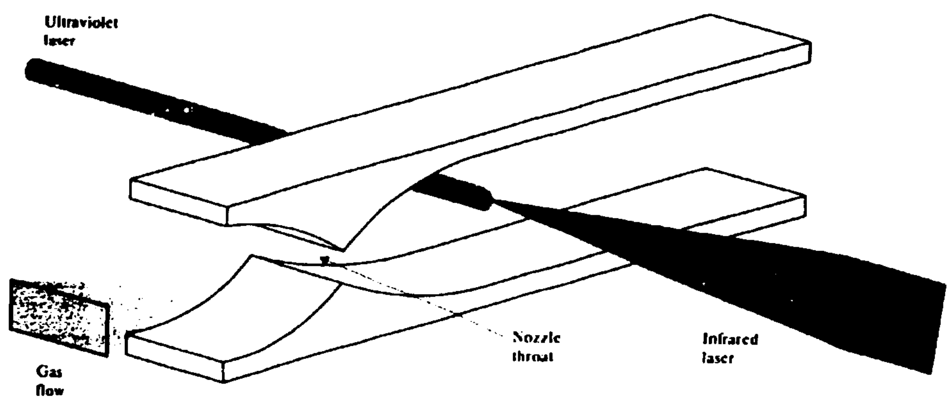
Figure 2
Molecular Laser Isotope Separation (MLIS) Setup



The UF_6 gas passes through the throat of the nozzle and expands. The resulting supercooled gas is irradiated by an infrared and then an ultraviolet laser.

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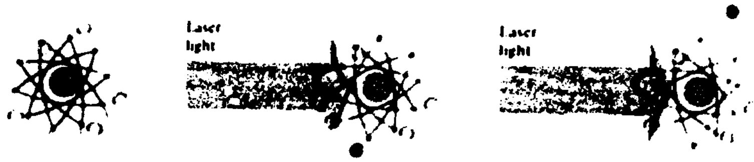
[redacted]

Figure 3
Atomic Vapor Laser Isotope Separation (AVLIS) Process



The electron energy states of the uranium atom are very precisely defined and depend on the mass of the nucleus. These energies give rise to light-absorption characteristics (energy level spectra, for example) that are unique to each isotope (that is, energy levels of different isotopes have an isotope shift).

When an isotope absorbs laser light precisely tuned to its discrete energies, its electrons are excited to higher states (that is, higher energy levels).

After the electron absorbs a sufficient amount of energy, it leaves the atom. This ionized atom has a positive charge which can be used to remove it from the rest of the vapor (or gas), which is not charged. For uranium separation it is the U-235 atoms that are ionized.

[redacted]

impractical. In order to overcome the problems caused by the thermal excitation of UF_6 molecules, it is necessary to cool the molecules to about 100 K. This supercooling can be done by supersonic expansion through a nozzle (figure 2). The introduction of a nozzle into the process, however, adds further complications. A production-plant-size nozzle must be carefully designed to allow sufficient flowthrough and to prevent condensation of the supercooled UF_6 gas. (If condensation is not prevented by nozzle design, additional lasers must be used to break up the condensation products.) In addition, the nozzle design is likely to necessitate that the laser beams propagate through large distances of gas. This condition causes serious problems associated with the degradation of laser beams and nonproductive losses of laser power. [redacted]

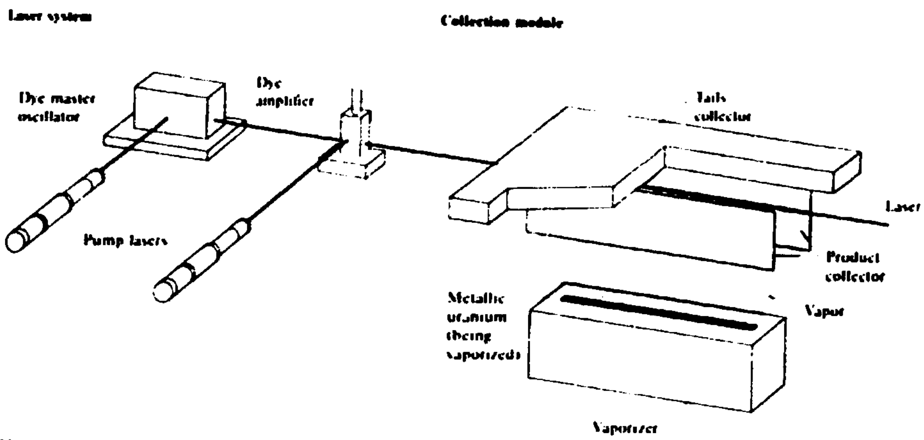
Because of the problems such as nozzle design, excessive laser powers, and new laser development, the US Government decided to develop a uranium AVLIS process instead of an MLIS process. The AVLIS technique involves the selective excitation and ionization of U-235 atoms (figure 3). The major difficulties involved in a uranium AVLIS process revolve around the use of high-temperature atomic uranium vapor and liquid. Atomic uranium is very reactive chemically and precautions must be taken to protect the components of the collection module (figure 4). In addition, the collector must be carefully designed so that the temperature of its components can be kept within a narrow range. [redacted]

A uranium LIS program for the development of a production plant would have four general phases: laser spectroscopy, experimental verification, process definition, and process demonstration [redacted]

In the laser spectroscopy phase, one would do an extensive study of the energy levels of UF_6 molecules (for the MLIS process) or uranium atoms (for the AVLIS process). The goal of this work is to locate

[redacted]

Figure 4
Atomic Vapor Laser Isotope Separation (AVLIS) Setup



Metallic uranium is melted and vaporized. It then expands into the collection module, where it is irradiated by visible laser light. The U-235 atoms are ionized and the ions are electromagnetically pulled onto collection plates.

[redacted]

energy levels with large cross sections (probabilities of excitation), long lifetimes, and sufficient isotope shifts. This information is needed to define the most efficient LIS process. The final experimental stage of this initial phase for an MLIS program would involve the high-resolution spectroscopy of supercooled UF_6 using laser diodes. For an AVLIS program, high-resolution laser spectroscopy has additional importance, because the major atomic energy levels of U-235 are split into several components. [redacted]

In the experimental verification phase, one would develop the equipment needed to perform isotope separation experiments on a laboratory scale. The experiments done with this equipment allow one to define the limitations and problems of the process. This experimental phase is particularly important for an MLIS process, because a complete theoretical understanding is lacking. For an AVLIS process, the experiments can be fully complemented by a theoretical program, because most of the important processes are understandable theoretically. It is expected that the laser spectroscopy and experimental verification phases would take from five to 10 years each if sufficient priority was given to them. Some overlap in time is possible for these two phases. [redacted]

The process definition and process demonstration phases involve the identification of equipment scalable to production-plant sizes, the development of such equipment, and its incorporation into a full-size test (or demonstration) module. These are the most difficult and crucial phases for an MLIS program. Assuming these phases can be completed, they are likely to take a total of 15 to 20 years. Some overlap in time with the experimental verification phase would be possible. [redacted]

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[redacted]