MODULE 3.0: LASER ENRICHMENT METHODS (AVLIS AND MLIS)

Introduction

Welcome to Module 3.0 of the Uranium Enrichment Processes Directed Self-Study Course! This is the third of seven modules in this directed self-study course. The purpose of this module is to provide a basic overview of laser enrichment process. Laser enrichment processes consist of two types: atomic, such as Atomic Vapor Laser Isotope Separation (AVLIS), and molecular laser isotope separation (MLIS). Atomic laser isotope separation (LIS) uses finely tuned lasers to preferentially ionize and remove one isotope. Molecular LIS uses finely tuned lasers to selectively change bond energies and electron states in molecules, thus forming a new molecule enriched in one isotope. LIS has achieved significant laboratory results. However, engineering and scale-up have proved difficult and no commercial LIS facilities are currently operating. This self-study module is designed to assist you in accomplishing the learning objectives listed at the beginning of the module. The module has activities and self-check questions to help you assess your understanding of the concepts presented in the module.

Before you Begin

It is recommended that you have access to the following materials:

- □ Trainee Guide

Complete the following prerequisite:

- □ Module 1.0 Introduction to Uranium Enrichment

How to Complete This Module

1. Review the learning objectives.
2. Read each section within the module in sequential order.
3. Complete the activities and self-check questions within this module.
4. Check off the tracking form as you complete each activity and/or the self-check questions within the module.
5. Contact your administrator as prompted for a progress review meeting.
6. Contact your administrator as prompted for any additional materials and/or specific assignments.
7. Complete all assignments related to this module. If no other materials or assignments are given to you by your administrator, you have completed this module.
8. Ensure that you and your administrator have dated and initialed your progress on the tracking form.
9. Go to the next assigned module.

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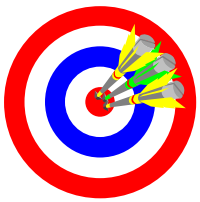


3.1 Upon completion of this module, you will be able to describe the Atomic Vapor Laser Isotope Separation (AVLIS) process.

3.1.1 Describe the principles of the AVLIS enrichment process.

3.1.2 Identify the facility description and component layout of the AVLIS process.

3.1.3 Identify the uses of the AVLIS process in industry and the required production amounts of enriched uranium.

3.1.4 Describe the principles and features of MLIS processes, such as SILEX.

3.1.5 Identify enrichment processes used internationally.

3.1.6 Identify the hazards and safety concerns for AVLIS and MLIS processes, including major incidents.

Learning Objective

When you finish this section, you will be able to:

3.1.1 Describe the principles of the AVLIS enrichment process.

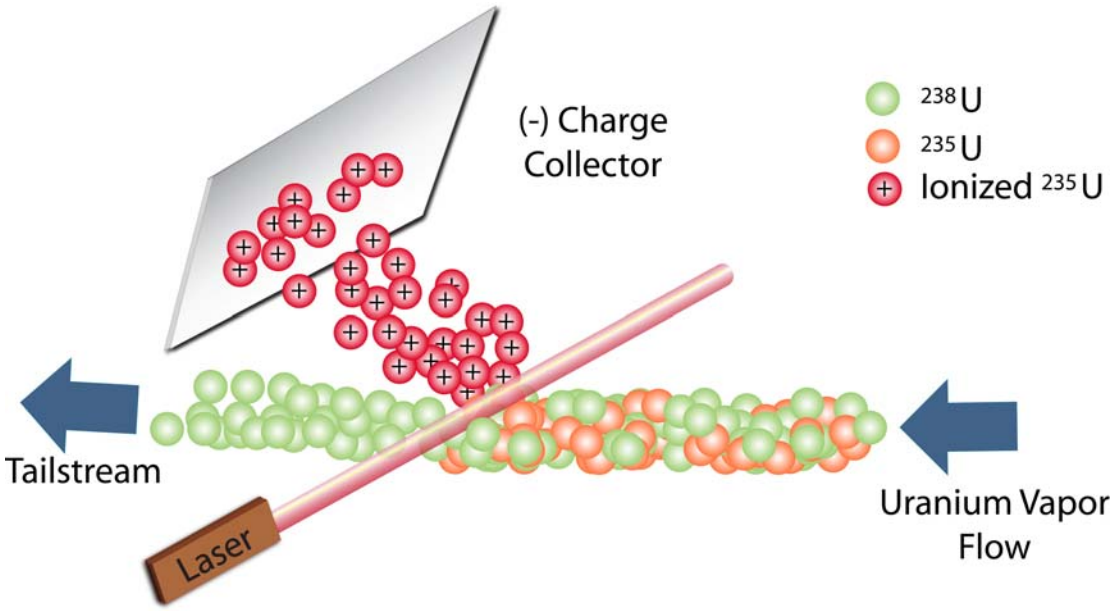
PRINCIPLE OF THE AVLIS PROCESS

Atomic vapor laser isotope separation (AVLIS) is a method of uranium enrichment that uses a laser to excite and ionize a uranium atom of a specific uranium isotope so it can be selectively removed. Uranium enrichment is the intermediate step in the nuclear fuel cycle that increases the concentration of uranium-235 relative to uranium-238 in order to make uranium usable as a fuel.

Nuclear Properties of Isotopes

All isotopes of the same element have nearly identical chemical properties, consequently separating these isotopes must rely on subtle effects created by the differences in mass of the atoms. Isotopes of every element also have unique spectroscopic "signatures" defined by the electromagnetic radiation (“light”) absorbed by their atoms from electron transitions. Atoms and molecules absorb light (e.g., from lasers) only at certain, well-defined wavelengths specific to each atomic or molecular species. Absorption at a particular wavelength leads to a well-defined change in the internal state of the molecular or atomic system, that is, the system is excited to higher vibrational, rotational, or electronic energy levels. Different isotopes of the same element absorb light at slightly different wavelengths. This isotope shift effect arises from the slight differences in the nuclear properties of the isotopes, including mass, shape, size, spin, and nuclear magnetic or electric moments. By finely tuning the irradiating light to coincide exactly with an absorption wavelength of one of the isotopic species, thus causing atoms of one isotope, but not the others, to undergo a change of state, the excited species may enter preferentially into chemical reactions, or respond preferentially to physical stimuli. For example, the standard AVLIS process uses multiple lasers to preferentially ionize uranium-235 and collect it electrostatically on a cathode. These minute differences between the light absorption properties of the isotopic species can be greatly magnified, and macroscopic isotope separation can then be achieved (Figure 3-1).

Figure 3-1. Simplified AVLIS Theory



Natural uranium is composed of three principal types, or isotopes: uranium-234, uranium-235 and uranium-238. As stated previously, only the uranium-235 is capable of sustaining fission, with thermal neutrons or atom splitting, which creates the energy to run a nuclear power plant. Natural uranium is composed of mostly uranium-238, and only about 0.7% uranium-235. So for uranium to be usable as nuclear fuel, the concentration of uranium-235 must be raised, or "enriched." In the most common types of nuclear reactors, a higher than natural concentration of uranium-235 is required.

The enrichment process produces this higher concentration, typically between 3.5% and 4.5% uranium-235, and currently must rely on subtle physical difference (e.g., mass, electrical charge) to produce separation. Theoretically, laser isotope separation (LIS) has the potential to achieve much larger isotope separation factors and, therefore, be a significant improvement.

Historic Beginnings of Laser Isotope Separation

The possibility of isotope separation using photochemical methods was first recognized in 1920, and the first successful experiment was conducted in 1932. The photochemical separation of uranium isotopes was studied under the Manhattan Engineer District, but it was found that it could not compete technically with gaseous diffusion when, then available, normal light sources were used for excitation. Not until lasers were developed did the concept begin to show promise in industrial application.
Lawrence Livermore National Laboratory (LLNL) began investigating

the use of lasers for isotope separation in the early 1970s. In 1974 after a bench scale experiment at LLNL successfully demonstrated enrichment, the AVLIS concept for uranium enrichment became one of the baseline approaches for development in the United States. In the mid 1970s, Union Carbide Corporation and then Martin Marietta Energy Systems, the operator of the Department of Energy (DOE) gaseous diffusion plants at Oak Ridge and Paducah, joined the AVLIS development team by bringing their expertise and experience in uranium handling.

Product concentrations of 3% to 5% uranium-235 can be obtained from natural uranium in a single pass through the separator device. Conceptually, AVLIS is capable of economically producing enriched uranium suitable for use in light water reactors from the stockpiles of depleted uranium resulting from the gaseous diffusion process.

AVLIS Process

AVLIS is based on the differences in atomic electron structure and offers the possibility of a higher degree of enrichment in a single step than do such processes as gaseous diffusion and the gas centrifuge (GC), which depend on small mass differences between the isotopes. Uranium-234 has a much shorter half-life than either U-235 or U-238, and thus has a high specific activity, considerably higher than the other naturally occurring isotopes. Ideally, enrichment should avoid increasing U-234 concentrations. Uranium-234 is enriched to a greater degree than uranium-235 by enrichment methods based on mass differences. However, the AVLIS process uses uranium metal vapor and a tuneable dye laser to selectively ionize uranium-235. In AVLIS, the dye laser is tuned to a frequency that will cause only the uranium-235 to ionize; no other uranium isotopes are affected. Therefore, not only is the enrichment of uranium-234 avoided, but its isotopic ratio is even lower in the product than in the feed material.

The AVLIS method of isotope separation depends on the quantum mechanical connection between energy and frequency in an atom's electrons. A laser is a device that can produce large numbers of photons, all having almost precisely the same frequency. Photons are defined as energy packets that compose electromagnetic radiation. AVLIS achieves separation of uranium-235 from uranium-238 by taking advantage of the slight difference in the energy of transition between the two isotopes. For uranium-235 and uranium-238 this spectrum difference is small, about 4.2×10^{-5} ev. This means that a laser beam must be tunable to an accuracy of 1 part of 10^5 in order to excite and ionize one of the isotopes (uranium-235) without affecting the other (uranium-238). By precisely tuning lasers to the spectrum (color) signature of a specific isotope, those atoms can be selectively photoionized and then electrically separated. Thus, once selectively ionized the separation of the U-235 isotope is enhanced. Multiple lasers are used to achieve ionization. The AVLIS process can, in principle, be used to separate isotopes of most elements.

The AVLIS process is designed to provide enrichments of uranium-235 to about 5% by the electrostatic extraction of laser-produced ions of uranium-235 from natural uranium. To provide the feedstock for the AVLIS process, metallic uranium or uranium alloy is melted and vaporized. AVLIS may also be cost-effective for further recovery of uranium-235 from DU tailings that have been stockpiled at gaseous diffusion plants.

The uranium metal vapor is illuminated by a laser that is precisely tuned to a wavelength that is absorbed by uranium-235 atoms, causing them to ionize. The ionized uranium-235 is deposited on product collectors, along with some of the natural uranium which is nonionized. However, most of the uranium-238 atoms go to a tailings collection system. The enriched uranium liquid metal condensate flows from the separator into a cast, where it is solidified. The enriched uranium is stored in solid form.

Enrichment processes like gaseous diffusion, thermal diffusion, and gas centrifuge use uranium hexafluoride (UF_6) vapor as the feed material. However, the AVLIS process uses metallic uranium metal vapor as the feed material because the electron levels and ionization states are well defined as compared to uranium compounds.

Basic Steps of AVLIS Process

Use of the major subsystems is reflected in the basic steps of the AVLIS method for enriching uranium. (Figure 3-2) The main steps are:

1. Conversion of U_3O_8 into UF_4
2. Conversion of UF_4 to a Uranium Iron Alloy
3. Solid-State Laser and Dye Laser Generation
4. Uranium Metal Vaporization
5. Excitation of Vaporized Metal
6. Collection of Product and Tails
7. Conversion of Metal Product to UO_2

Step 1. Conversion of U_3O_8 into UF_4

This step involves the dissolution of U_3O_8 in nitric acid (HNO_3) to produce a uranyl nitrate solution. This solution then goes through filtration, solvent extraction, and is re-extracted to obtain a clear, pure uranyl nitrate solution. After concentration and denitration, UO_3 is produced. UO_3 is then reduced with hydrogen (H_2) to UO_2. A fluorinator reacts its UO_2 with gaseous HF, producing solid UF_4 (greensalt). The material is ground to a fine powder.

Step 2. Conversion of UF_4 to a Uranium Iron Alloy

AVLIS plans were to build a new facility to convert the UF_4 to uranium–iron alloy. UF_4 requires reducton to uranium metal. This is normally accomplished by magnesium reduction.

The greensalt powder and magnesium shavings are packed into a steel pressure vessel (sometimes called a "bomb"). The vessel is sealed and placed in a furnace. Upon heating to an ignition temperature, a rapid temperature increase occurs from the magnesium–UF_4 reaction. Liquid uranium metal coalesces to the bottom of the vessel, while magnesium fluoride floats to the top. After cooling the uranium metal, "derby" is physically separated. Continuously operating variations have been developed on a small scale.

In the U.S., U_3O_8 is normally purified by UF_6 distillation. Therefore, the UF_4 initially produced by HF fluorination is further fluorinated with elemental fluorine to form UF_6. The UF_6 is recovered as a vapor, condensed to a liquid, and distilled. After distillation, the UF_6 is vaporized and reacted with hydrogen to form UF_4 again, for feed to the magnesium reduction.

Step 3. Solid-State Laser and Dye Laser Generation

The pump laser for the AVLIS process is the solid-state laser (SSL). It utilizes a solid (i.e., Nd-YAG crystal) as the lasing medium. The pump laser converts electrical energy into light energy. This light energy is used to energize, or "pump," the AVLIS process laser. The process laser, in turn, provides the specific frequency light needed to photoionize U^{235} vapor in the AVLIS process. The process laser, known as a dye laser, uses fluorescent dyes dissolved in alcohol to convert "raw" pump laser light into precisely tuned process light.

In order to obtain selective excitation, the wavelength of the laser beam frequency must coincide with the absorption spectrum of interest for uranium-235 and not coincide with absorption feature of uranium-238. The line width of the excited state must be narrow with respect to the isotope shift. Isotope shifts in the atomic uranium vapor absorption spectrum are typically in the range of 0.05 to 0.1 angstrom.

As previously mentioned, the dye lasers contain dyes dissolved in alcohol. The dye molecules cannot be electrically driven and in the AVLIS process they are energized by exciting flashes of green-yellow light from the solid-state laser. The dye absorbs the light from the solid-state laser and re-emits it over a broad range of colors. A single dye can produce many shades of red and orange light so the wavelength must be "tuned" to the desired wavelength within the frequency band by using optical components. The dye laser beam is amplified in stages to the power level required for efficient ionization of the uranium-235 vapor. The laser beam is optically reflected through the photoionization chamber many times, possibly as many as 300 times. A total of up to three colors are used to ionize the uranium-235 atoms.

Step 4. Uranium Metal Vaporization

Uranium vapor must be produced at extremely high temperatures. This is performed by melting uranium metal in a crucible using a beam of electrons directed to the surface of the ingot by a magnetic field. Sometimes a uranium–iron alloy has been tested because of its lower melting eutectic as compared to the pure uranium. The molten uranium is extremely corrosive, and elaborate systems are required to keep it from contacting the support structures and to prevent rapid dissipation of heat supplied to the uranium ingot. The molten uranium provides a line source of uranium atoms that diverge radially outward toward the photoionization region at the top of the chamber. The uranium atoms move undisturbed through the lower portion of the chamber and lose much of the excess energy they received during their evaporation. This gets them into their lowest energy states and allows ions formed by the electron beam to recombine into neutral forms. Only about 50% of the evaporated atoms reach the photoionization zone; the remainder are deposited on various surfaces and this material must be periodically collected and recycled.

Step 5. Excitation of Vaporized Metal

The vapor that reaches the irradiation zone is illuminated by laser light precisely tuned to excite transitions in uranium-235 but not in uranium-238. Several lasers, with slightly different wavelengths in the red-orange portion of the spectrum, are used in a three-step ionization of the uranium-235 (see Figure 3-3). In the first step, two laser beams of slightly different wavelengths are used to excite the uranium-235 in the ground state or low-lying excited state. Subsequent excitation results in an electron's being rejected from the uranium-235 atoms producing a positive ion. The laser beam is slowly attenuated as it traverses the illumination path within the separation module. This causes its effectiveness for ionizing uranium-235 to drop and it usually becomes more economical to discard the degraded laser beam and to introduce a new one. An economic tradeoff between the cost of introducing an additional laser beam versus the decrease in performance determines the optimum number of sectors in the system.

The uranium atoms that do not absorb the light from the laser beam remain nonionized and largely pass through the product collector system to the tailings collector.

Figure 3-2. Basic Steps of AVLIS Process

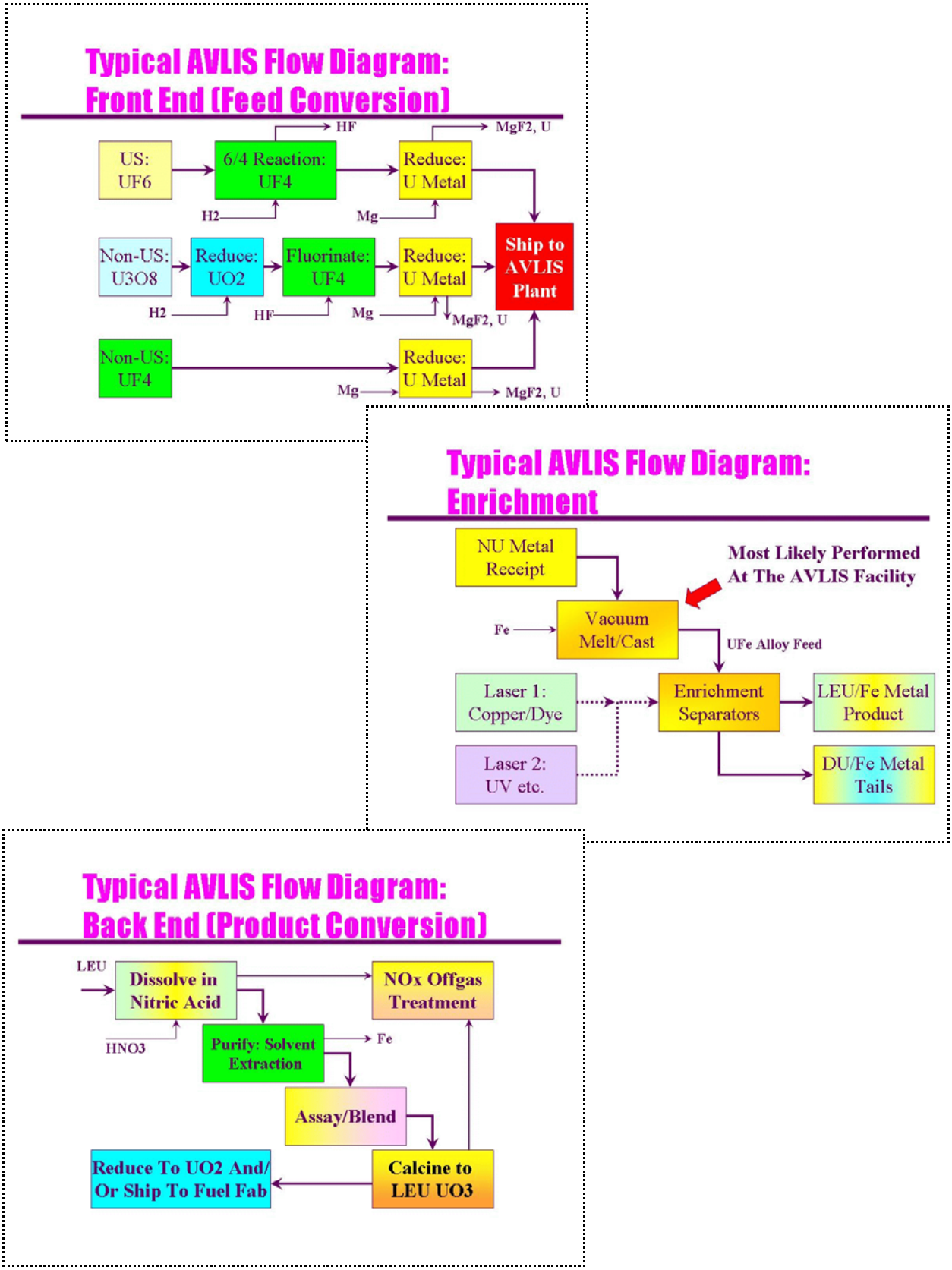
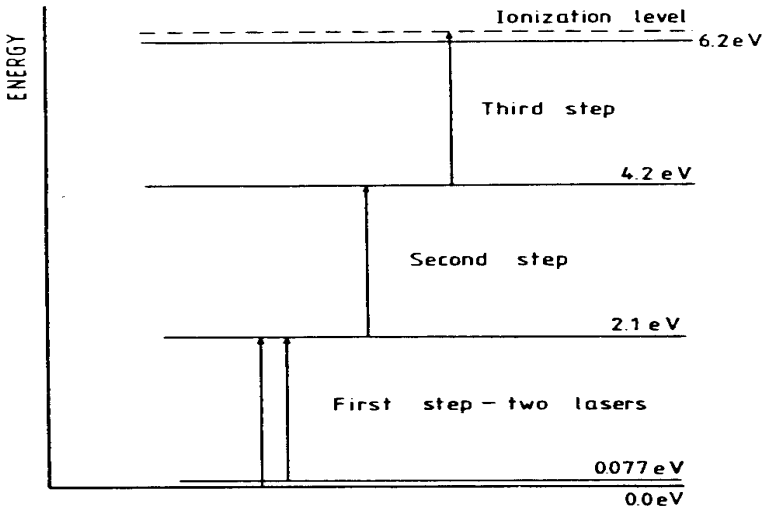


Figure 3-3. Three-Step Laser Ionization of Uranium-235 (Source: Krass, el al., 1983)



Step 6. Collection of the Product and Tails

An electromagnetic field is used to drive the ionized uranium-235 to the product collector plates. A portion of the upstreaming vapor that contains nonenriched uranium is carried by the uranium-235 vapor motion and also deposits on the collector plates, limiting the degree of enrichment attained.

The vapor that is not ionized by the laser light and does not deposit on the product collector plates moves through the extractor zone. It accumulates as depleted uranium tails and becomes a separate stream.

The surfaces onto which both the tails and the product are collected operate at elevated temperatures. The uranium metal product and the tails condense and flow as liquid uranium metal into separate collection systems.

Step 7. Conversion of Metal Product to UO_2

The plan for AVLIS product conversion was to build a new product conversion facility that would convert a uranium–iron alloy to uranyl nitrate ($[UO_2 (NO_3)_2]$) and then convert to UO_2. This would be accomplished possibly by directly dissolving the metal product in nitric acid or oxidizing and then dissolving. The resulting uranyl nitrate solution would then go through purification (filtration, solvent extraction), denitration, and reduction to UO_2.

Characteristics of Laser Isotope Separation Processes

The laser-based isotope separation processes, AVLIS and Molecular Laser Isotope Separation (MLIS), are expected to provide commercial production of low-cost separative work in the future. Both processes tend to be very high-tech in nature and appear to require extensive and expensive research programs for their development. See Table 3-1 for the LIS process characteristics.

Table 3-1. LIS Process Characteristics

Separation Factor Per Stage	2 - 6
Energy Consumption	100 - 150 kWh/SWU
Specific Inventory	Very Low
Equilibrium Time for 3% Uranium-235 Product	Very Short
Process Fluid	Uranium Metal (AVLIS) UF_6 (MLIS)
Facility Size	Small - Moderate
Process Equipment	Laser Systems Optical Systems Separation Module System

General Conditions Necessary for Laser Isotope Separation

In order to use laser isotope separation, six general conditions must be met:

- The initial energy level configuration must allow the selective excitation of the desired isotope.
- The absorption spectrum of the material must contain at least one well-defined shift in an absorption line due to isotopic effects.
- The exciting laser light source must be precisely tunable to the wavelength of the shifted line (that is, atoms and molecules absorb light only at well-defined wavelengths; the wavelengths of the laser beam must coincide with the absorption wavelength), be stable at that wavelength, and have a line width that is narrow compared to the magnitude of the isotopic shift effect.
- The laser must be sufficiently efficient and powerful to provide a reasonable yield without excessive energy demand.
- The energy and/or charge exchange losses between the excited component and the rest of the system should be small.

- The separation process should be sufficiently selective and capable of producing a good yield of the desired isotope.
- Environmental, safety, and health parameters are met.

Advantages of Using Lasers for Isotope Separation

Lasers show several advantages over conventional light sources for the purpose of isotope separation:

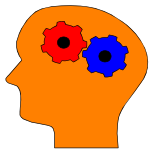
- Laser light is tunable over a wide range of frequencies, increasing the probability that the source frequency can be made to coincide with an absorption resonance frequency in the desired isotopic species.
- Laser light is very highly monochromatic, facilitating the selectivity requirement that the bandwidth of the exciting source is narrower than the isotope shift.
- The very high intensity of laser light within these narrow bandwidths permits large process throughputs.
- The ability to generate laser radiation in the form of pulses, whose duration can be much shorter than the lifetime of the excited state, increases the efficiency of practical applications, wherein the excited atoms must be exposed to a second (and sometimes a third) irradiation before they decay.
- The high collimation achievable with laser radiation permits long optical paths in reaction cells, increasing process throughput.

Benefits of AVLIS

The potential benefits of AVLIS/MLIS separation are numerous. It is projected to be an energy efficient uranium enrichment process, using only about 5% of gaseous diffusion's energy use. The enrichment occurs in one pass through the separator, unlike the hundreds or thousands of cycles needed by the other techniques. Also, the need for conversion to uranium hexafluoride is gone, making the process potentially simpler, safer, and less expensive. The avoidance of UF_6 also eliminates the fluoride waste occurring in other methods.

AVLIS is projected to use 95% less electricity and 20 to 30% less natural uranium than current gaseous diffusion technology to produce each separative work unit (SWU). Separative work is a measure of the effort expended in a uranium enrichment plant to separate uranium of a given uranium-235 content into two components, one having a higher percentage of uranium-235 and the other a lower concentration. USEC estimated that AVLIS production costs would be $30 per SWU lower than gaseous diffusion. Energy consumption for the AVLIS process is dependent on the efficiency of the laser used, which is generally low, on the order of 0.1%.

Activity 1 - Principles of the AVLIS Process



Purpose: The purpose of this activity is to identify the principles of the AVLIS process.

Instructions: Complete the following activity. Answers are located in the answer key section of the Trainee Guide.

1. Natural uranium is composed of three types, or isotopes:_____, _____ and _____.

2. The quantum theory states that _____ consists of a large number of energy packets known as photons, and the energy in every packet is proportional to the frequency of radiation.

3. Of which characteristic does the AVLIS program take advantage?

4. Six general conditions must be met in order to use laser isotope separation. Fill in the missing word(s) for each condition.

   - The initial energy level configuration must allow the selective excitation of the desired_____.
   - The absorption _____ of the material must contain at least one well-defined shift in an absorption line due to isotopic effects.
   - The exciting laser light source must be precisely _____ to the wavelength of the shifted line (that is, atoms and molecules absorb light only at well-defined wavelengths; the wavelengths of the laser beam must coincide with the _____ wavelength), be stable at that wavelength, and have a line width that is narrow compared to the magnitude of the isotopic shift effect.
   - The laser must be sufficiently efficient and powerful to provide a reasonable yield without excessive_____ demand.
   - The energy and/or charge exchange losses between the excited component and the rest of the system should be_____.

- The_____ process should be sufficiently selective and capable of producing a good yield of the desired isotope.

5. Number the following basic steps as they occur in the AVLIS process.

   _____ Excitation of Vaporized Metal

   _____ Solid-State Laser and Dye Laser Generation

   _____ Conversion of UF_4 to a Uranium–Iron Alloy

   _____ Uranium Metal Vaporization

   _____ Conversion of Metal Product to UO_2

   _____ Conversion of U_3O_8 into UF_4

   _____ Collection of Product and Tails

6. A single dye can produce many shades of red and orange light so the wavelength must be _____ to the desired wavelength within the frequency band by using optical components.

Self-Check Questions 3-1

Complete the following questions. Answers are located in the answer key section of the Trainee Guide.

1. AVLIS is an enrichment process in which lasers are used to selectively ionize uranium-235 in a photochemical process to allow it to be separated from _____ .

   a. uranium-234
   b. uranium-236
   c. uranium-238
   d. uranium hexafluoride

2. Which uranium isotope is capable of sustaining fission?

   a. uranium-234
   b. uranium-235
   c. uranium-236
   d. uranium-238

3. AVLIS is a quantum process based on _____ and offers the possibility of a higher degree of enrichment in a single step than do such processes as gaseous diffusion and the gas centrifuge, which depends on _____.

   a. large mass differences between the isotopes; differences in atomic or molecular structure
   b. differences in atomic or molecular structure; large mass differences between the isotopes
   c. small mass differences between the isotopes; differences in atomic or molecular structure
   d. differences in atomic or molecular structure; small mass differences between the isotopes

4. In AVLIS, the dye laser is tuned to a frequency that will cause the uranium-235 to ionize but not other uranium isotopes; thus, not only is the enrichment of uranium-234 avoided, but its isotopic ratio is _____.

   a. lower in the feed material than in the product.
   b. higher in the product than in the feed material.
   c. lower in the product than in the feed material.
   d. the same in the product and in the feed material.

5. In the AVLIS process, what is the range of product concentrations of uranium-235 obtained from natural uranium in a single pass through the separator device?

   a. .1 to .3%
   b. .3 to .5%
   c. 1 to 3%
   d. 3 to 5%

6. Which of the following devices can produce large numbers of photons, all having almost precisely the same frequency?

   a. Laser
   b. Cyclotron
   c. Separator
   d. Gas Centrifuge

7. Which uranium enrichment process uses metallic uranium vapor as the feed material?

   a. AVLIS
   b. Gas Centrifuge
   c. Thermal Diffusion
   d. Gaseous Diffusion

8. The quantum theory states that _____ consists of a large number of energy packets known as photons, and the energy in every packet is proportional to the frequency of radiation.

   a. matter
   b. uranium
   c. radiation
   d. electrons

9. For isotopes of every element, what is defined by the colors of light absorbed by their atoms?

10. What does the pump laser do in the AVLIS Process?

11. What does the process laser provide in the AVLIS process?

12. The molten uranium is extremely _____, and elaborate systems are required to keep it from contacting the support structures and to prevent rapid dissipation of heat supplied to the uranium ingot.

    a. hot
    b. emollient
    c. corrosive
    d. radioactive

13. The uranium atoms move undisturbed through the lower portion of the chamber and lose much of the excess energy they received during their _____ .

14. What percentage of the evaporated atoms reach the photoionization zone?

    a. 40%
    b. 45%
    c. 50%
    d. 60%

You have completed this section.
Please check off your progress on the tracking form.
Go to the next section.

Learning Objective

When you finish this section, you will be able to:

3.1.2 Identify the facility description and component layout of the AVLIS process.

FACILITY DESCRIPTION

An Atomic Vapor Laser Isotope Separation facility will include an advanced enrichment process that uses lasers to enrich vaporized uranium metal.

Figure 3-4. An AVLIS Module (Source: Krass et al., 1983)

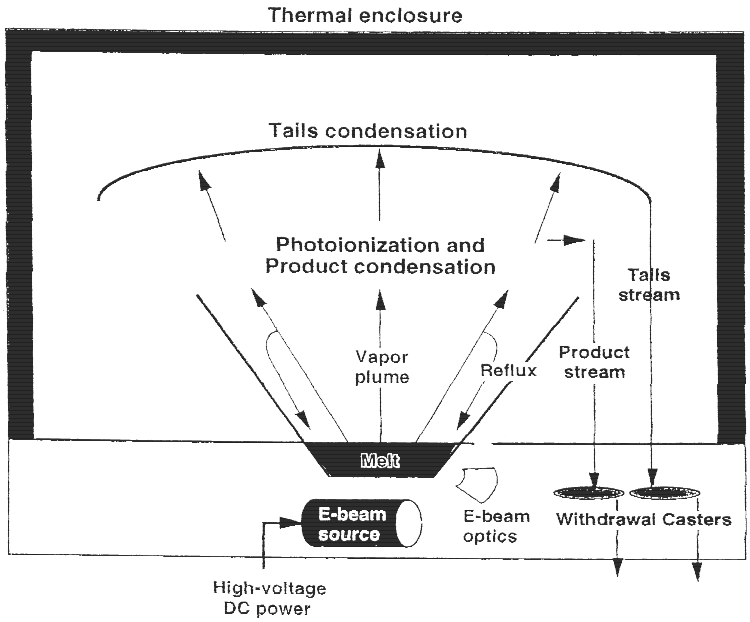


Figure 3-4 shows the principle of an AVLIS module. Uranium vapor is produced by electron beam evaporation from the crucible at the bottom. The vapor expands outward until it reaches the irradiation region where the uranium-235 atoms are excited and ionized by laser light. The ions are deflected and collected on the vertical plates by a combination of electric and magnetic fields. Neutral atoms continue outward and are collected on the horizontal plate at the top. The laser light is shown being reflected several times through each collection volume by a system of mirrors.

Equipment and

Equipment and components that have been specially designed or

Components

prepared for AVLIS are as follows:

1. High power strip or scanning electron beam guns with a delivered power of more than 2.5 kW/cm for use in uranium vaporization systems;

2. Liquid uranium metal handling systems for molten uranium or uranium alloys, consisting of crucibles, made of or protected by suitable corrosion and heat resistant materials (e.g. tantalum, yttria-coated graphite, graphite coated with other rare earth oxides or mixtures thereof), and cooling equipment for the crucibles (usually water cooling);

3. Product and tails collector systems made of or lined with materials resistant to the heat and corrosion of uranium metal vapor or liquid, such as yttria-coated graphite or tantalum;

4. Separator module housings (cylindrical or rectangular vessels) for containing the uranium metal vapor source, the electron beam gun, and the product and tails collectors; and

5. Lasers or laser systems for the separation of uranium isotopes with a spectrum frequency stabilizer for operation over extended periods of time.

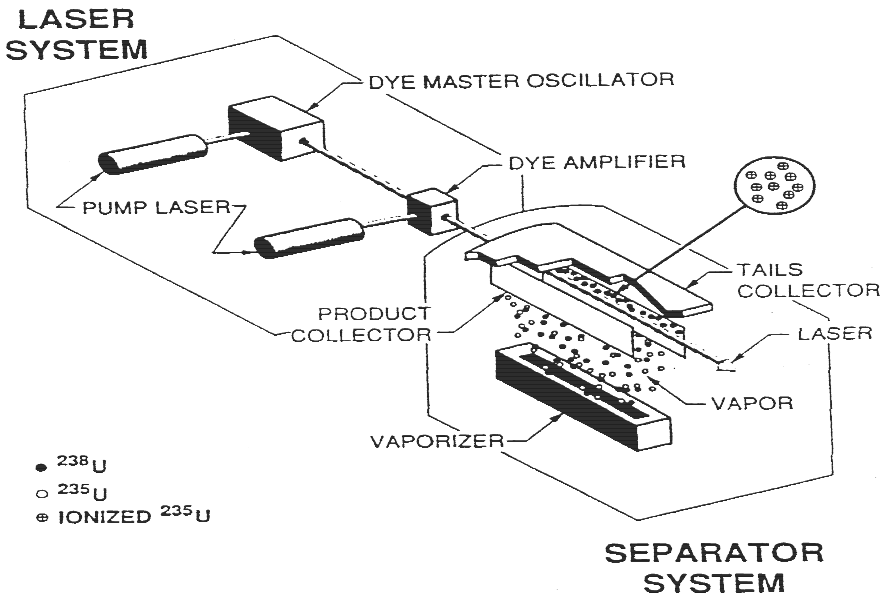
Major Subsystems

The two major subsystems of the AVLIS process are: (see Figure 3-5).

- Separator system
- Laser system

The laser system is physically outside the radioactive materials handling areas and the light beams are, transmitted by optical tubes to the AVLIS separations. This provides for easier maintenance.

Figure 3-5. AVLIS Process

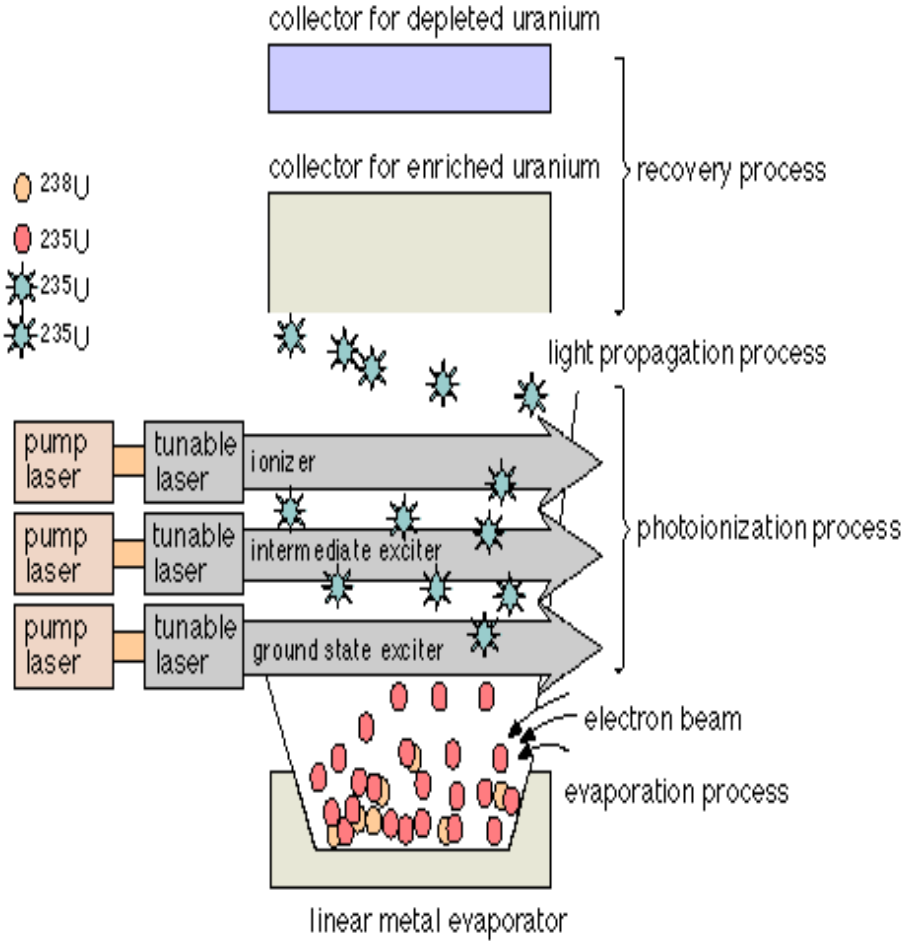


Separator System

The AVLIS process for enrichment of uranium uses molten uranium metal, rather than UF_6. The uranium metal alloy feedstock is vaporized by an electron beam and bombarded by a laser beam to ionize the uranium-235 atoms and separate them from the uranium-238 in an electrostatic field. This process produces an enriched product stream and a depleted tails stream.

The separator system contains a vaporizer and a collector (see Figure 3-6). Primary uranium metal is introduced into a large vacuum vessel where it is melted and vaporized (at about 3400°C) by large electron beam guns to form an atomic vapor stream. A very high-voltage power supply is required for this process. (The interaction of these electrons with the uranium melt produces copious quantities of X-rays.) The vapor stream flows through the collector, where it is illuminated by precisely tuned laser light. Uranium atoms in this vapor are then selectively ionized by laser light. When the laser light illuminates the uranium vapor, only the uranium-235 atoms absorb the light. When a uranium-235 atom has absorbed enough light, it ejects an electron, thus becoming a positively charged atom, which can then be deflected by an electromagnetic field to the product collector. The majority of the uranium-238 atoms remain neutral and pass through the collector section to the tails collector.

Figure 3-6. Separation Process



The uranium-235 atoms that lose an electron become positively charged. These positive uranium-235 ions are attracted to the collector plates. The uranium-235 enriched uranium vapor is condensed to liquid that flows to a product collection mold. The product stream is formed by collecting these ions, as well as a portion of the feed material, on negatively charged collector plates. The non-ionized uranium-238 atoms continue outward and are collected on the horizontal plate at the top.

Uranium depleted in uranium-235 forms the tails stream. This process takes place in a vacuum chamber in which the uranium is vaporized and exposed to the lasers. The product ions are extracted electromagnetically on product collectors, while the tails stream passes through to be collected on a tails collector. The product collectors (plates) are maintained at an elevated temperature to keep the uranium-235 and uranium-238 liquid; the product and tails are allowed to flow to sealed pots under the vacuum. These pots are left attached to the system long enough to fill and solidify the uranium liquid, then moved off in dollies or carts for storage or other potential use. The laser light is reflected several times through each collection volume by a system of mirrors. Both enriched and depleted uranium streams are removed as small nuggets of solid uranium metal.

Laser System

In the separation process, the laser system uses finely tuned, high-power solid-state laser system and dye lasers to selectively ionize the uranium vapor. The lasers are tuned to the correct frequency with the proper wavelength and number of wavelengths necessary to cause ionization of just the uranium-235 atom (product ions). The uranium-238 atom stays neutral in the vaporized uranium (tails stream). The vapor stream flows through the collector where it is illuminated by precisely tuned laser light. When the laser light illuminates the uranium vapor, only the uranium-235 atoms absorb the light. When the uranium-235 atom has absorbed enough light, it ejects an electron, thus becoming a positively charged atom.

Some components of the laser system are:

- pump lasers
- dye lasers
- dye amplifiers
- beam propagation optics
- thyratrons/magnetic switches
- high-voltage energy storage capacitor

The solid-state lasers are packaged in individual boxes that contain the support systems necessary for their operation and are connected at stations along the optical support structure. The modular characteristics of the laser system allow a redundancy that prevents total system shutdown in case of failure in any one unit. The AVLIS solid-state lasers are joined together in master oscillator power amplifier (MOPA) chains that supply laser power to the dye lasers.

The lasers are pulsed in operation and must turn on and off several thousand times each second. Each pulse lasts less than one-millionth of a second, so precise timing of the laser pulses is needed. The dye lasers usually use alcohols or flammable solvents. Additionally, the laser and optical systems must be able to withstand high-power laser illumination for long periods of time while maintaining high-quality optical properties.

Title 10 CFR Part 110 Applicability

Title 10 CFR Part 110, “Export and Import of Nuclear Equipment and Material” is subject to NRC enforcement action. Appendix F to Part 110, “Illustrative List of Laser-Based Enrichment Plant Equipment and Components Under NRC Export Licensing Authority”, provides a list of equipment and components to be considered during the licensing and inspection processes. The following are excerpts that relate directly to the AVLIS process:

"Present systems for enrichment processes using lasers fall into two categories: the process medium is atomic uranium vapor and the process medium is the vapor of a uranium compound. Common nomenclature for these processes include: first category-atomic vapor laser isotope separation (AVLIS or SILVA); second category-molecular laser isotope separation (MLIS or MOLIS) and chemical reaction by isotope selective laser activation (CRISLA). The systems, equipment and components for laser enrichment plants include:

(a) devices to feed uranium-metal vapor for selective photoionization or devices to feed the vapor of a uranium compound for photo-dissociation or chemical activation;
(b) devices to collect enriched and depleted uranium metal as 'product' and 'tails' in the first category, and devices to collect dissociated or reacted compounds as 'product' and unaffected material as 'tails' in the second category;
(c) process laser systems to selectively excite the uranium-235 species; and
(d) feed preparation and product conversion equipment. The complexity of the spectroscopy of uranium atoms and compounds may require incorporation of a number of available laser technologies.

"All surfaces that come into contact with the uranium or UF_6 are wholly made of or protected by corrosion-resistant materials. For example, the materials resistant to corrosion by the vapor or liquid of uranium metal or uranium alloys include yttria-coated graphite and tantalum; and the materials resistant to corrosion by UF_6 include copper, stainless steel, aluminum, aluminum alloys, nickel or alloys containing 60% or more nickel and UF_6-resistant fully fluorinated hydrocarbon polymers.

"Many of the following items come into direct contact with uranium metal vapor or liquid or with process gas consisting of UF_6 or a mixture of UF_6 and other gases:

"(1) Uranium vaporization systems (AVLIS).
Especially designed or prepared uranium vaporization systems that contain high-power strip or scanning electron beam guns with a delivered power on the target of more than 2.5 kW/cm.

"(2) Liquid uranium metal handling systems (AVLIS).
Especially designed or prepared liquid metal handling systems for molten uranium or uranium alloys, consisting of crucibles and cooling equipment for the crucibles.

The crucibles and other system parts that come into contact with molten uranium or uranium alloys are made of or protected by materials of suitable corrosion and heat resistance, such as tantalum, yttria-coated graphite, graphite coated with other rare earth oxides or mixtures thereof.

"(3) Uranium metal 'product' and 'tails' collector assemblies (AVLIS).
Especially designed or prepared 'product' and 'tails' collector assemblies for uranium metal in liquid or solid form.

Components for these assemblies are made of or protected by materials resistant to the heat and corrosion of uranium metal vapor or liquid, such as yttria-coated graphite or tantalum, and may include pipes, valves, fittings, 'gutters', feed-throughs, heat exchangers and collector plates for magnetic, electrostatic or other separation methods.

"(4) Separator module housings (AVLIS).
Especially designed or prepared cylindrical or rectangular vessels for containing the uranium metal vapor source, the electron beam gun, and the 'product' and 'tails' collectors.

These housings have multiplicity of ports for electrical and water feed-throughs, laser beam windows, vacuum pump connections and instrumentation diagnostics and monitoring with opening and closure provisions to allow refurbishment of internal components."

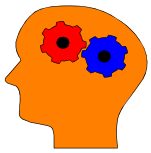
"(13) Lasers or Laser systems (AVLIS, MLIS and CRISLA).
Especially designed or prepared for the separation of uranium isotopes. The laser system for the AVLIS process usually consists of two lasers: a copper vapor laser and a dye laser. The laser system for MLIS usually consists of a CO_2 or excimer laser and a multi-pass optical cell with revolving mirrors at both

ends. Lasers or laser systems for both processes require a spectrum frequency stabilizer for operation over extended periods."

NRC Licensing of AVLIS

USEC suspended work on the AVLIS project in June 1999. USEC does not expect to submit an ALVIS application to the NRC. If the AVLIS project had continued, the NRC would have had regulatory authority over the AVLIS plant. NUREG-1701, “Standard Review Plan for the License Application for the Atomic Vapor Laser Isotope Separation (AVLIS) Facility,” was drafted for comment. It was developed to provide guidance to the NRC reviewers who will perform safety and environmental reviews of any license application for a AVLIS facility under 10 CFR Part 70.

Activity 2 - Components of the AVLIS Process



Purpose: The purpose of this activity is to review the facility description and components of the AVLIS process.

Instructions: Complete the following activity. Answers are located in the answer key section of the Trainee Guide.

1. What is contained in the separator system?

2. List some of the components of the laser system.

3. Which regulation addresses the Export and Import of Nuclear Equipment and Material?

   a. 10 CFR Part 110
   b. 15 CFR Part 774
   c. 29 CFR Part 1910
   d. 47 CFR Part 1

Self-Check Questions 3-2

Complete the following questions. Answers are located in the answer key section of the Trainee Guide.

1. What are the two major subsystems of the AVLIS process?

2. A vaporizer and a collector are part of the _____ system.

3. The uranium metal alloy feedstock is vaporized by an electron beam and bombarded by a laser beam to ionize the uranium-235 atoms and separate them from the uranium-238 in an electrostatic field. What is the outcome of the process?

4. What drives the ionized uranium-235 to the product collector plates?

5. What happens to the uranium atoms that do not absorb the light from the laser beam?

6. What is the duration of each pulse of the laser?

   a. Less than one-hundredth of a second
   b. Less than one-thousandth of a second
   c. Less than one-millionth of a second
   d. Less than ten-millionth of a second

7. An Illustrative List of Laser-Based Enrichment Plant Equipment and Components is provided in which of the following?

   a. Appendix C to Part 110
   b. Appendix D to Part 110
   c. Appendix E to Part 110
   d. Appendix F to Part 110

You have completed this section.
Please check off your progress on the tracking form.
Go to the next section.

Learning Objective

When you finish this section, you will be able to:

3.1.3 Identify the uses of the AVLIS process in industry and the required production amounts of enriched uranium.

INDUSTRIAL USES OF THE AVLIS PROCESS WORLDWIDE AND RELATED PRODUCTION AMOUNTS OF ENRICHED URANIUM

Many countries have pursued some level of AVLIS research and/or development, and major programs have existed in the United States, France, and Japan. Principal potential advantages of the AVLIS process include a high separation factor, low energy consumption, and a small volume of generated waste. No country has yet deployed an AVLIS process, although several have demonstrated the capability to enrich uranium with the process. While conceptually simple, the actual implementation of the process is likely to be difficult and expensive, especially for countries with limited technical resources. The AVLIS process requires much sophisticated hardware constructed of specialized materials that must be capable of reliable operation for extended periods of time.

United States: Uranium-Atomic Vapor Laser Isotope Separation

The uranium-atomic vapor laser isotope separation (U-AVLIS) Program began in 1973 to help maintain the U.S. market share of supplying the world's enrichment services. The program was developed to produce uranium enriched in the uranium-235 isotope, which was needed to fuel fission reactors. The program goal was to provide the world's lowest-cost uranium-enrichment method for commercial power-plant fuel. As previously discussed, USEC suspended the AVLIS project in June 1999. The following is a brief history of the program.

The first U-AVLIS enrichment demonstration was conducted in 1974. Using a refractory metal oven to produce vaporized uranium, the Morehouse experiment produced milligram quantities of enriched uranium, verifying the physics of the AVLIS process for the first time at Lawrence Livermore National Laboratory (LLNL) (see Figure 3-7). A combination of lasers, resonance optical radiation, and electrostatic ion collection were used. This was the starting point for the LLNL-developed process. Subsequent increases in the scale and efficiency over the next several years were needed to show commercial promise.

In 1980, a few years after the proof-of-principle experiments at microscopic scale, a larger, gram-scale experiment using electron beams to vaporize uranium and more powerful lasers successfully separated several grams of enriched uranium at an enrichment of a

few percent. This was achieved with the REGULIS separator (see Figure 3-8). Based on an electron beam evaporation process, this unit was the next step in reaching practical production levels.

Figure 3-7. The Morehouse Experiment Produced Milligram Quantities of Enriched Uranium for the First Time

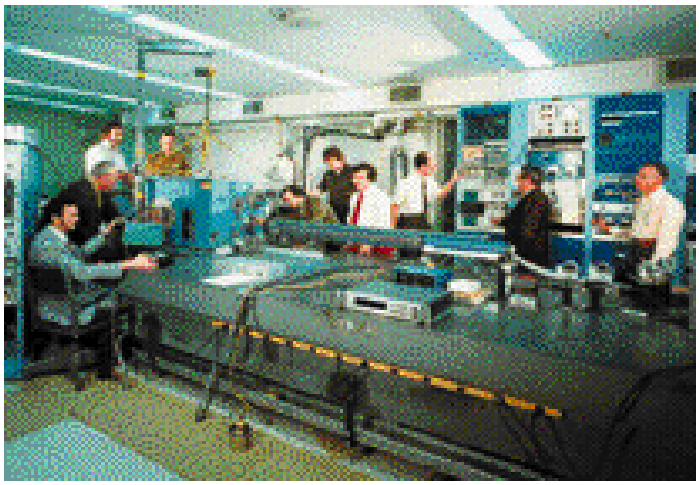
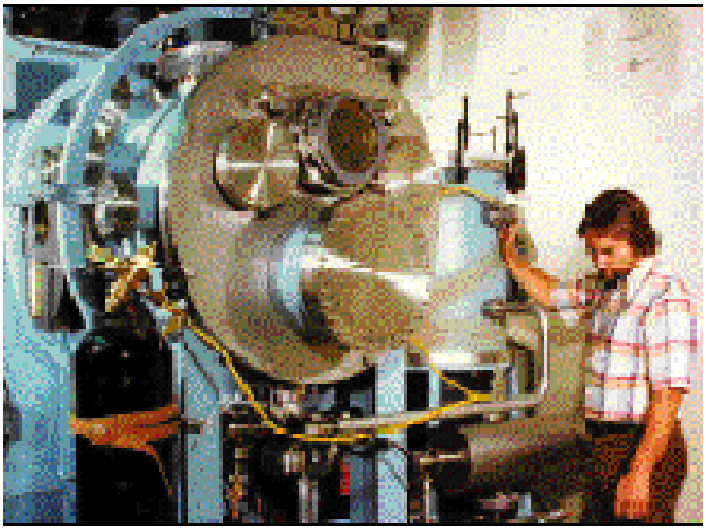


Figure 3-8. The REGULIS Separator Successfully Separated Several Grams of Enriched Uranium



Continued scale-up of the lasers and separators culminated in experiments in uranium and plutonium at practical-use scale. At the MARS Facility, where fractions of metric tons of uranium were processed, the assays and product masses developed were high enough that economic projections of industrial-scale implementation of this technology became realistic. At the same time, the lasers were scaled to near-plant operating parameters. These components were key to economic production of high-power laser light needed to operate a commercial plant.

In 1985, the DOE chose AVLIS as its enrichment technology of the future. The AVLIS process was developed under a contract with DOE by the LLNL located in Livermore, California.

The Uranium Demonstration System (UDS) and the Laser Demonstration Facility (LDF) at LLNL were constructed to test the U-AVLIS process at plant scale and were the basis for developing a complete plant conceptual design.

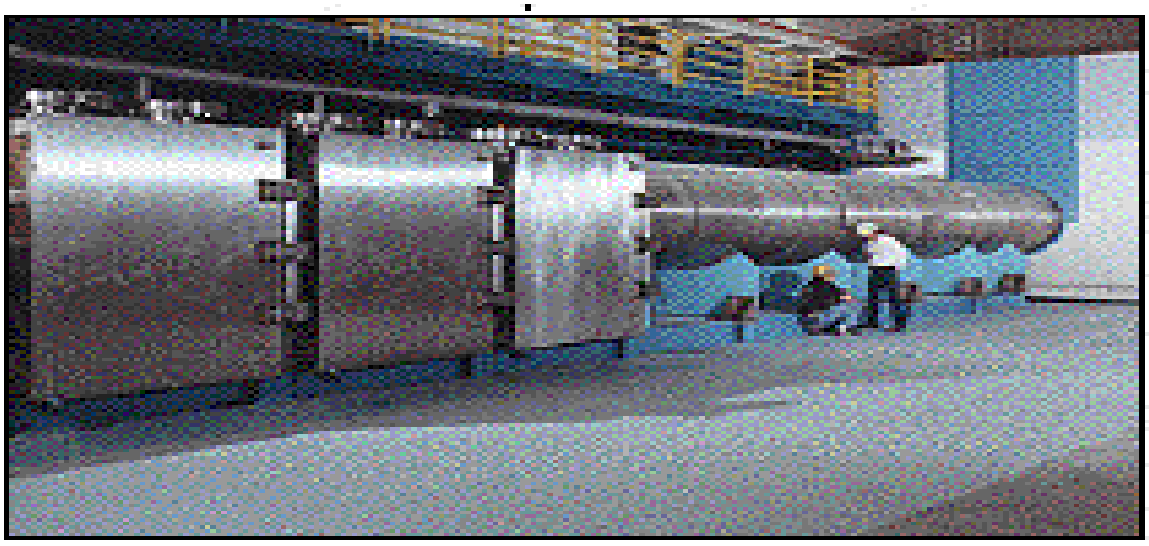
The Energy Policy Act of 1992 granted the USEC exclusive commercial rights to deploy AVLIS. Development, demonstration, design activities and final testing were scheduled at LLNL as well as other support activities at General Electric Company in Wilmington, North Carolina and Cameco Corporation in Port Hope, Ontario, under the direction of the USEC. On July 1, 1993, the U.S. Government uranium enrichment activities were transferred from the U.S. Department of Energy to the USEC. The USEC was privatized in July 1998.

The AVLIS Program funded by the USEC represented the largest and most significant technology transfer activity in the history of LLNL. USEC is presently a public corporation supplying enrichment services to the nuclear fuel industry using existing gaseous diffusion plants located in Kentucky and Ohio. AVLIS was to offer USEC a lower-cost option for enriching uranium to meet customer demand.

USEC had planned to open the first commercial AVLIS plant, capable of producing 8.7 million SWUs per year, along with the feed (uranium-iron alloy) plant and uranium dioxide conversion plant, by 2005. However, USEC suspended all AVLIS project work in 1999 because data indicated the returns were not sufficient to outweigh the risks and ongoing capital expenditures necessary to develop and construct an AVLIS plant. USEC still retains the rights and patents to the AVLIS process. USEC had also secured the exclusive rights to explore the commercial viability of the Separation of Isotopes by Laser Excitation (SILEX) enrichment process. Subsequently USEC canceled its agreements on the SILEX process. In addition, USEC intends to also explore the gas centrifuge process and base its new enrichment facilities on gas centrifuge technology.

The major building blocks of the AVLIS process are the separation chambers, laser and optical systems, computer controls, and uranium handling systems. See Figure 3-9.

Figure 3-9. Plant-scale Uranium Separator System



The separation process uses finely tuned, high-power lasers to ionize the fissile isotope of uranium, uranium-235, by removing one of its electrons. A positive uranium-235 ion results. The product stream is formed by collecting these ions as well as a portion of the feed material on charged plates. Uranium depleted in uranium-235 forms the tails stream. This process takes place in a vacuum chamber in which the uranium is vaporized and exposed to the lasers. Both streams are removed as small nuggets of solid uranium metal. Further chemical processing and fabrication yields finished fuel for use in nuclear power reactors. Also, the program successfully completed isotope enrichment tests using gadolinium and established several new business options based on AVLIS technologies. Natural gadolinium is currently used as a burnable neutron absorber in light-water nuclear power plants. The use of an isotopic mixture enriched in its odd isotopes improves the safety and economics of light-water reactor operations.

Laser Activities

Laser technology development continued to support the future deployment of an AVLIS plant. Efforts continued to eliminate the chlorofluoro carbons (CFCs) used to cool electronic components in the copper laser system. The latest laser oscillator eliminates CFCs in favor of air and water cooling, and the newest amplifier eliminates CFC cooling of the high-voltage power supply. The amplifier pulse-power modulator is a challenge because of its high average power

(nearly 100 kW), high output voltage (80 kV), and short risetime (tens of nanoseconds). Tests of oil-cooled modulators were completed.

A full-scale version of an AVLIS plant's dye laser module has been installed and activated. All copper laser pump light is supplied by large-core optical fibers. Hybrid telescopes with refractive/refractive lenses (which reduce the dye chain's length as much as 50%) transport dye laser beams through the optical system. Alignment of both the copper and dye laser beams is remotely monitored and controlled.

Separator Activities

Operations of the separator pod for gadolinium vaporization and modifying the electron-beam magnetic transport system to minimize the magnetic field in the photozone have been completed. The pod operated smoothly and easily produced the desired gadolinium vaporization rates, and together with the laser systems, supported successful enrichment demonstrations.

On activating the next-generation uranium separator pod, the run duration (more than 250 hours) and throughput rate (near plant value) achieved by the earlier generation pod in 1993 were records for AVLIS and represented important steps toward the program goal of 600-hour pod lifetimes.

The new pod was redesigned or modified for 19 of 23 key components and subsystems in an effort to reduce complexity, part count, and cost. The 90-hour pod test in June 1995 was the first since 1993, and it enabled evaluation of a large number of design changes needed for the plant. Nearly all these new designs were successful and were carried over to the next scheduled test.

Efforts in this key area were focused on engineering and demonstrating separators for reliable operations and enrichment performance. The Separator Demonstration Facility (SDF) was reactivated in December 1995 to progressively meet performance goals. Verification of near plant-level enrichment in a series of integrated separator and laser demonstrations began in early 1998.

Three separator tests were initiated increasing the total cumulative test time by 50% over prior testing in the 1991–1993 time frame. These demonstrations led to important design and operations advances including (1) automated control of the uranium vaporizer at near-plant rates, (2) testing of improved materials for reliable liquid uranium containment and flow, (3) identification of a need for uranium feed with low impurity content, and (4) closed-loop control of thermal systems.

To prepare for frequent (~2-month interval), long-duration separator testing, off-shift operators and refurbishment staff were hired and

trained. Significant support logistics for procurement, planning, and parts inventory was also initiated.

Lasers and Optics Activities

All laser systems were activated, including the dye process lasers and copper lasers used to energize these systems. Three plant prototype copper laser chains were activated, and a single-chain output of 1300 watts (86% of plant goal) was demonstrated for long duration. In addition, the reliability growth of the high-average power pulsed electrical power supply was sufficient to allow demonstration of a mean time between failure at 60% of the plant goal.

A plant prototypic dye laser chain was operated at greater than 80% plant power goals averaged over the 500-hour test duration. This test achieved all objectives including average power, peak power, efficiency, and availability in 500 hours, and indicates significant progress made toward engineering systems necessary for successful plant operation.

In parallel with these single-chain dye laser tests, the number of dye chains and associated optical systems in the Laser Demonstration Facility (LDF) were doubled from two to four chains in preparation for near-plant enrichment level demonstrations, which were scheduled for 1998. A new industrial-based computer control system was also installed and activated.

Plant Design Activities

General arrangement designs for the plant separator and laser buildings were completed and the key designs for plant interface control and system design requirements were documented. The plant computer control system requirement specifications were also initiated and over one-third were completed.

Current Status

After USEC suspended the AVLIS program, facilities were maintained in a standby mode for several years. Most of these facilites are now being decommissioned.

Self-Check Questions 3-3

Complete the following questions. Answers are located in the answer key section of the Trainee Guide.

1. The U-AVLIS program in the United States began at what national laboratory?

2. What act granted USEC exclusive commercial rights to deploy AVLIS?

3. While conceptually simple, the actual implementation of the AVLIS process is likely to be difficult and expensive due to what requirement?

Learning Objective

When you finish this section, you will be able to:

3.1.4 Describe the principles and features of MLIS processes, such as SILEX.

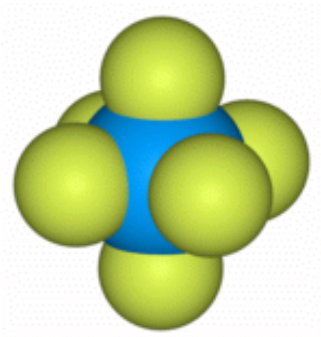
MOLECULAR LASER ISOTOPE SEPARATION

The molecular laser isotope separation (MLIS) process is related to AVLIS; however, the process medium is different (see Figure 3-10 and 3-11). In MLIS, the absorption of photons occurs in a molecular species of uranium such as UF_6. Molecules have vibrational transitions that allow photon absorption at very specific energies. Thus, possibility exists for isotopically selective absorption only in the uranium-235 constituent of the molecular uranium mixture. Isotopically selective excitation can be accomplished by irradiating the U-bearing molecules with a low-power beam of carefully tuned laser light (see Figure 3-12). More energy is added to the excited molecules until there is a chemical change in the original ^{235}U-bearing module. Such a chemical change or fragmentation of the original molecule is called dissociation. Known uranium compounds have absorption spectra with transitions in the far infrared (IR) where the equivalent photon energy is of order 0.01 to 0.1 electron volts (eV).

The dissociation energy of molecules is of order a very few eV. Many IR photons are needed to excite and dissociate the molecule. Attempts have been made to accomplish strep with ultraviolet (UV) photons which have a few eV per photon.

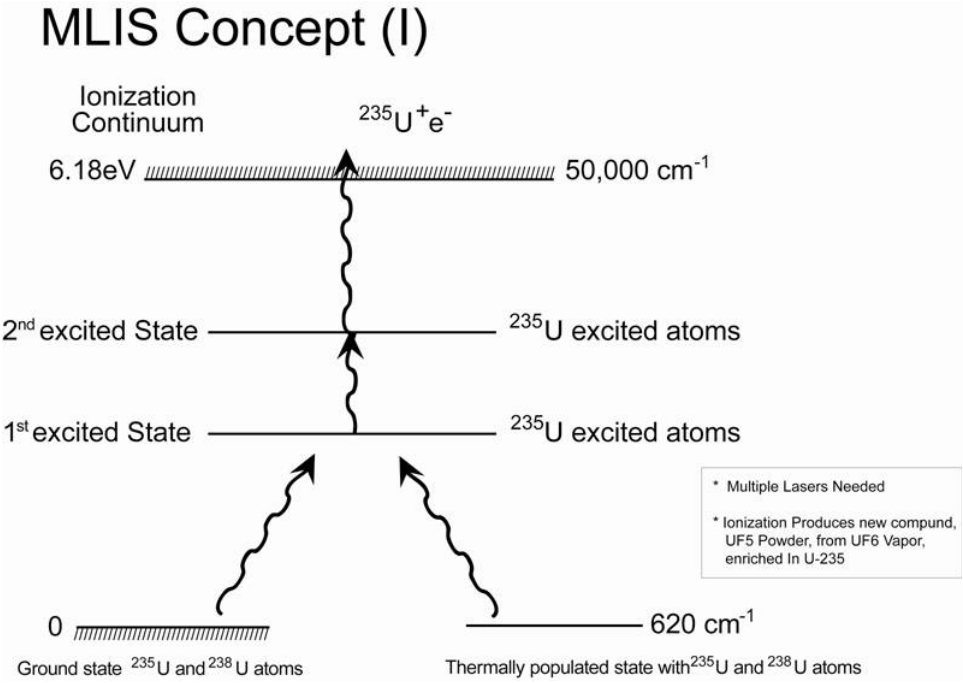
UF_6 molecules have a central uranium atom enclosed in an octahedral "cage" comprised of six fluorine atoms (see Figure 3-10).

Figure 3-10. UF_6 Octahedral "cage" Comprised of Six Fluorine Atoms



An isotopically selective transition occurs at about 16µm wavelength, which serves as the isotopically selective laser frequency. One or more IR photons in the 16µm band may be added as the absorption process broadens and shifts the transition frequency in the longer wavelength (red) direction. The dissociation step requires the addition of 3.2 eV per molecule and the result is production of UF_5 and a fluorine atom. It can be accomplished by a high-power beam of either IR or UV. The U.S. Program used UV dissociation; all other known versions of the MLIS process have chosen IR dissociation.

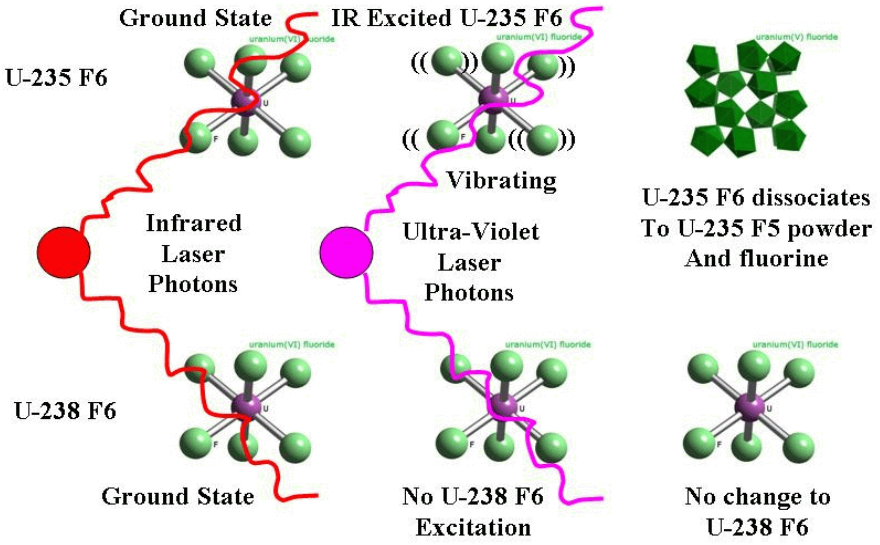
Figure 3-11. MLIS Concept I



*** Multiple lasers needed**
*** Ionization produces new compound, UF5 powder, from UF6 vapor**

MLIS process research has extensively focused on the use of uranium hexafluoride due to its prevalence in the nuclear industry and its well known properties. Figure 3-12 depicts one approach for MLIS processing of UF_6. UF_6 has uniform bonds (often referred to as d^2sp^3 hybrid bonds). The fluorine atoms occupy the points of an octahedron. Molecular differences in UF_6 accrue only from uranium because fluorine has only one stable isotope. Selective infrared laser excitation results in additional vibrations in the $U(235)F_6$ with no effect upon $U(238)F_6$. Additional laser excitation produces so much vibration that the $U(235)F_6$ molecule loses a fluorine atom and dissociates into $U(235)F_5$; it also liberates fluorine gas. Unlike UF_6, UF5 has a very low volatility, and, thus, it nucleates and forms a fine powder ("snow"). This solid powder is enriched in uranium-235 and can be physically separated from the remaining (and now depleted) UF_6 vapor.

Figure 3-12. MLIS Concept II



Practical application of MLIS requires several operating conditions. First, low temperatures (usually cryogenic levels) are used because of the cleaner electron spectrum so obtained and reduced kinetics of refluorination. Second, a carrier gas dilutes the UF_6 vapor (pure UF_6 would desublime; dilution also improves separation efficiency by reducing collisions and refluorination). Third, rapid separation of the fine powder from the UF_6 (and liberated fluorine) is needed to avoid mixing and refluorination. Often a scavenging gas is added to the carrier gas to consume free fluorine or fluorine radicals. Figure 3-13 shows a concept for an MLIS separator where expansion through a nozzle produces the cryogenic temperatures and the powder is separated by flow effects.

Figure 3-13. MLIS Separator

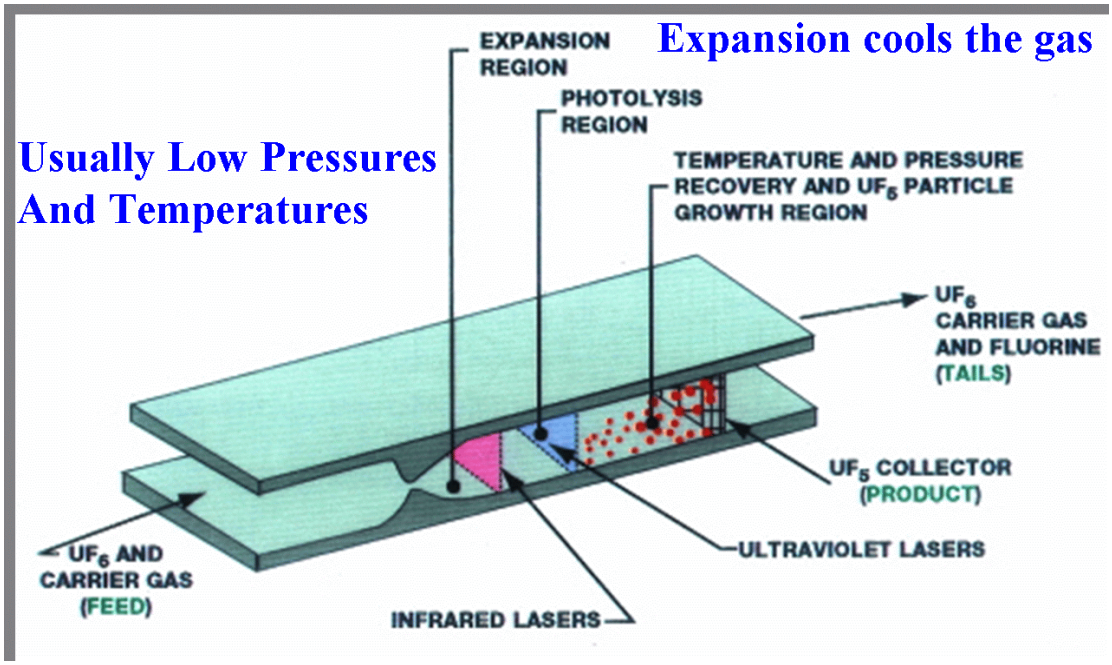
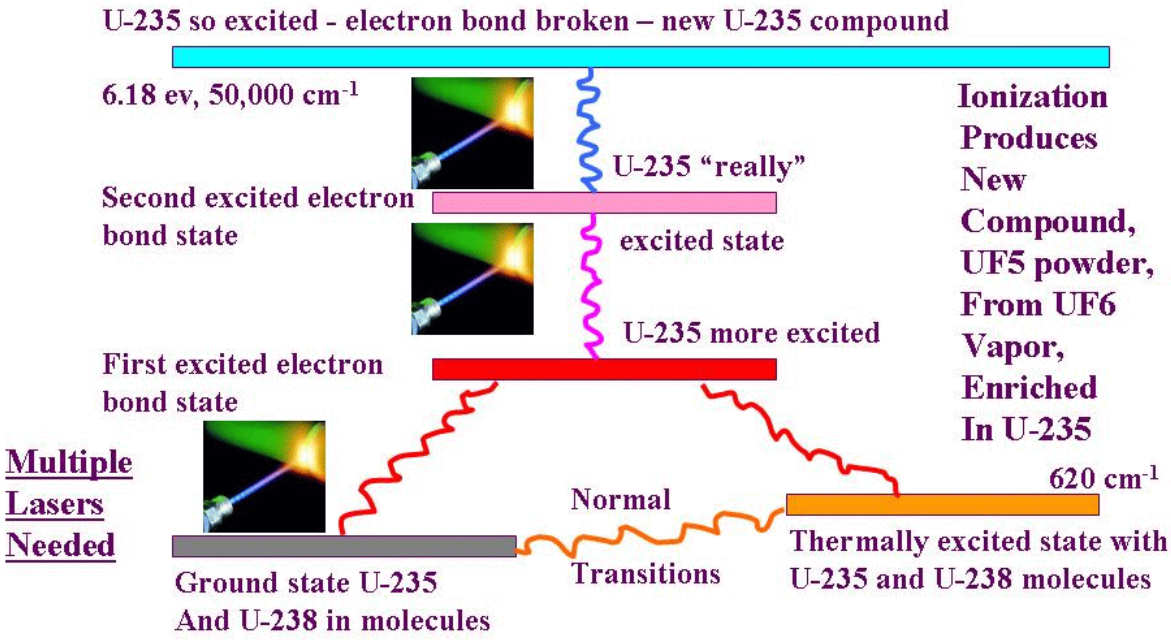
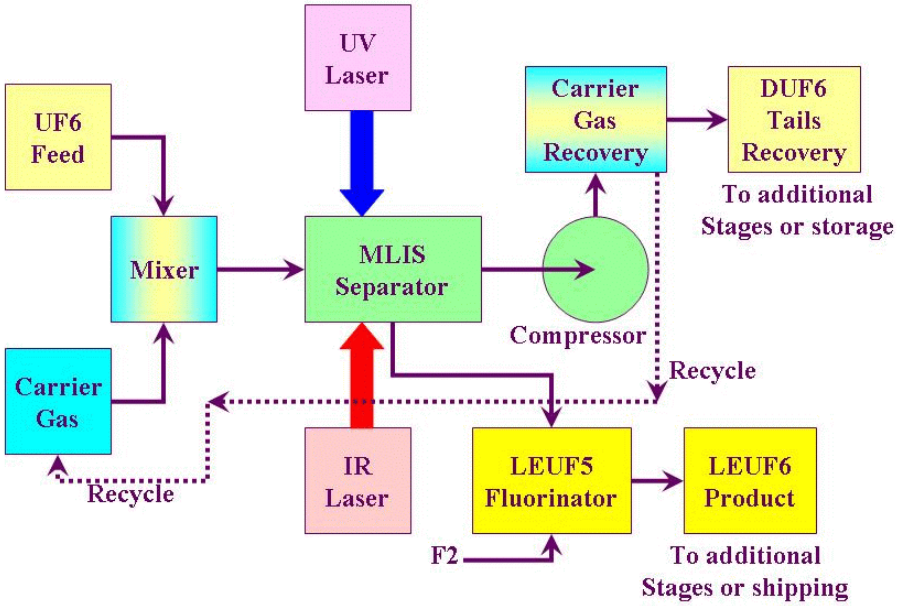


Figure 3-14 depicts an example of an MLIS process block diagram. After dilution and mixing in a carrier gas, such as argon or helium, expansion through a nozzle and diffuser cools the gas mixture to cryogenic temperatures of approximately -180 C. Multiple lasers selectively excite the U(235)F_6 and produce the (now enriched) U(235)F5 fine powder "snow." Flow effects separate the powder from the gas stream. Other unit operations include heat exchangers and gas purification; for example, UF_6 is removed by the carrier gas using condensation or desublimation. Inefficiencies will likely result in several stages being required for an adequate enrichment level in the product LEU.

Figure 3-14. MLIS Process Concept and Example





MLIS processes, including SILEX (Selective Isotope Enrichment by Laser Excitation), are still in the R&D stage. There is little information on ES&H issues and these will likely require significant attention. MLIS processes need to address some concerns similar to AVLIS, such as removal of solids, separator cleanout, efficiency versus throughput, and laser reliability. In addition, UF_6 handling hazards exist, but these may be similar to those of the GC processes and, consequently, easily manageable.

SILEX uranium enrichment has been under development for a significant time period with initial developments some 30 years ago on stable isotopes and detections. Efforts on SF_6 instrumentation ultimately led to developments involving $UF_{6.}$ Initially, SILEX (the company) developed the process using private funds and grants. SILEX signed an agreement with USEC for further development, ultimately leading to a commercial deployment. Tests were conducted and progress payments made by USEC. USEC concluded the SILEX process was 2-5 years away for an application to the NRC. USEC subsequently canceled the agreement with SILEX in 2002 in order to focus on GCs.

SILEX continued work on the process and successfully completed the "direct measurement program." This achieved enrichment and supported "attractive economics," but no specifics were given. SILEX and the Australian and American governments concluded classification agreements on the SILEX technology. In May 2006, General Electric and SILEX entered into an agreement for further testing, scale-up activities, a test loop demonstration facility, and, possibly, commercial deployment.

The GE-SILEX agreement provides for a phased approach to the commercialization of SILEX technology and the potential construction of a commercial enrichment facility. The agreement is funded by GE and testing and/or commercial facilities could be built at GE's site in Wilmington, North Carolina, or several other domestic sites under evaluation. GE has exclusive rights to the SILEX technology and, in return, will make a series of scheduled payments to the SILEX company as specific technology development milestones are reached; ultimately, GE would make royalty payments to SILEX generated by commercial operations using the SILEX technology.

Any domestic testing or commercial facilities for SILEX technology using radioactive materials would be regulated by the NRC and would require a Part 70 license. A commercial SILEX facility would be defined as an "enrichment facility" per Part 70, and, as such, has hearing and environmental impact statement (EIS) requirements. By analogy to the licensing of commercial GC facilities a SILEX commercial plant review might require an elapsed time of three years. In contrast, licensing of test facilities would probably involve a shorter review timeframe and perhaps reduced hearing and environmental reviews.

MLIS is the UF_6-based process being developed in Japan. Until recently, South Africa and France were involved in the industrialization of the MLIS technology for the commercial enrichment of uranium under multiple intergovernmental agreements.

Self-Check Questions 3-4

Complete the following questions. Answers are located in the answer key section of the Trainee Guide.

1. What is the basis for MLIS?

2. Why do MLIS processes often use cryogenic temperatures?

3. What uranium compound is often used in MLIS?

4. What is a typical U-235 reaction product or intermediate in MLIS?

5. Why is a carrier gas used?

6. What does a scavenger gas do?

You have completed this section.
Please check off your progress on the tracking form.
Go to the next secion.

Learning Objective

When you finish this section, you will be able to:

3.1.5 Identify laser enrichment processes used internationally.

INTERNATIONAL ACTIVITIES ON LIS

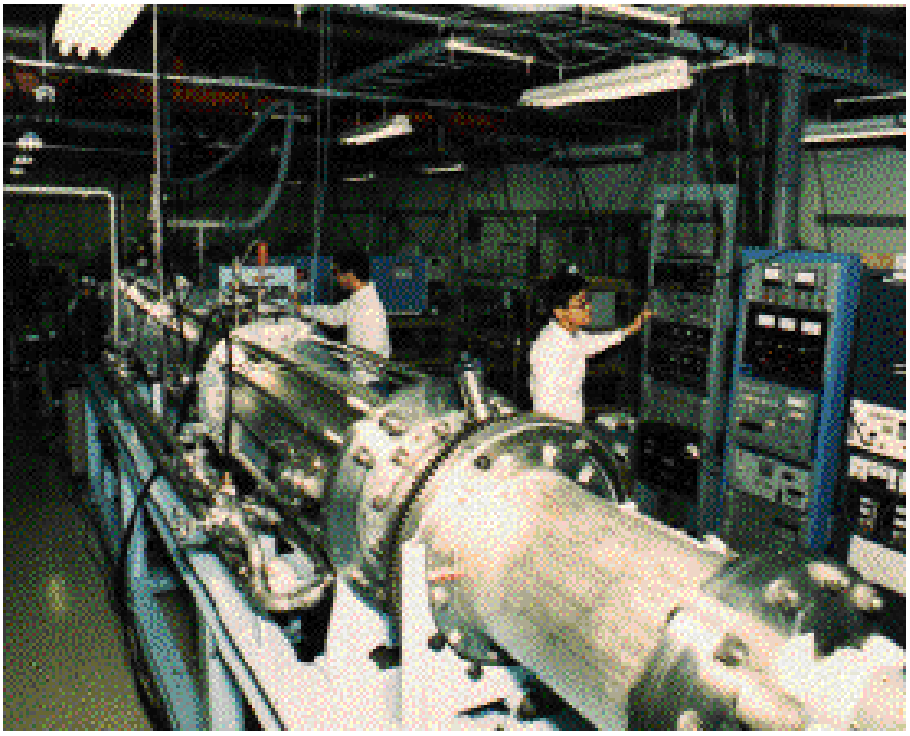
LIS of uranium isotopes has been experimentally pursued in many countries, including Japan, France, Australia, South Korea, Brazil, and Iran. Gram quantities of LEU and, in some cases, HEU, have centrifuge enrichment processes. At the present time, the SILEX (LIS) process developed in Australia is receiving the most attention. Very little effort is currently being devoted to other laser enrichment processes. This section briefly discusses the more extensive programs of Japan, France, and Australia.

Japan: Riken's Molecular Laser Isotope Separation and AVLIS

A unique uranium enrichment process, RIKEN's Molecular Laser Isotope Separation (RIMLIS) has been developed by the Molecular Laser Isotope Separation Group. Gaseous $^{235}UF_6$, cooled below 100 K in a supersonic nozzle reactor, is dissociated by powerful multi-frequency Raman lasers (see Figure 3-15) at 16 mm to form $^{235}UF_5$ nano-particles. The current research objectives of this group are aimed at 16 mm laser development using new concepts and on building more cost-effective reactors having high UF_6 density.

Researchers in Japan have also conducted research and development on AVLIS enrichment. This process, called Laser-J, was very similar to the U.S. AVLIS approach. Uranium-235 is selectively excited using tunable lasers. The resulting ionized atoms are separated electromagnetically. While laser enrichment would consume the least power of any enrichment technique, it is still complex and difficult. Development has been slowed by technical problems, by mounting oversupply in the enrichment market, and the commericial success of GC enrichment technology. These have resulted in less urgency and decreased funding for LIS in Japan.

Figure 3-15. Highpower 16µ*m* Laser System for RIMLIS



France Separation

The uranium enrichment process represents 10% of the kilowatt/hour cost of nuclear generated electricity. Today the focus has turned toward a third uranium enrichment system using lasers.

With the help of several companies, such as Gec-Alsthom, Sagem, Matra, Snecma, and Cilas, the French Atomic Energy Commission (CEA) is developing a new enrichment process using lasers to halve the cost of the separation work-unit compared to the cost of a technology developed 20 years ago and used in industry (gaseous diffusion). The first report on the process, dubbed SILVA (Séparation Isotopique par Laser de la Vapeur Atomique d'Uranium), was scheduled to be drafted in 1997.

The first stage of the SILVA system is to evaporate metallic uranium at 3000°C with an electron beam. CEA has installed three test benches, Apis, Anubis, and Amon at Pierrelatte as part of SILVA system development. They can determine optimum configuration of the uranium crucible as well as the shape of the beam spot (Apix), they can fine-tune the physico-chemistry of the process (Anubis), and test various electron gun settings (Amon).

Once the uranium vapor is produced, it is then "sorted" in a separator where the vapor is bombarded with laser photons tuned to several, very specific computer-adjusted wavelengths. During this stage, only uranium-235 atoms are ionized. The objective for each laser chain is

to meet power requirements and produce a spectrum quality to within one millionth for several hundred hours. A fourth test bench, also at Pierrelatte, dubbed the "C100 laser arm," can now test an entire chain equipped with Cilas power (100 watts) copper vapor laser modules, coupled with coloring lasers that produce the ionizing photons.

Now the "enriched" uranium has to be collected onto lateral plates and the "depleted" uranium onto the separator "dome." This is done at 1200°C, a temperature where liquid uranium is particularly corrosive. Research scientists are working on optimizing the materials used in the process at the Iris facility at Pierrelatte.

Industrial deployment of SILVA continues to be scheduled for the next decade. Once each system operation is fully controlled and optimized, all systems will be operational at the Saclay facility, called Aster3, in the Paris Region. Small scale testing of the entire SILVA system began in 1996. If everything goes as planned, a demonstration facility, designed with Cogema, will become operational in the twenty-first century.

SILVA has already produced extremely positive results. In 1990 a small quantity of uranium was enriched by 5%. A year later, a dozen grams of enriched uranium were separated. And then the Maeva evaporator at Pierrelatte ran continuously for 100 hours. France is still maintaining a low level of effort on LIS and SILVA.

Australia: Separation of Isotopes by Laser Excitation

Silex Systems Limited is an Australian research and development company that owns the proprietary rights to a laser-based isotope separation process known as the SILEX technology. SILEX is the acronym for Separation of Isotopes by Laser Excitation.

Isotope separation has a number of commercial applications, including uranium enrichment, an important step in the production of fuel for the nuclear electricity industry. Other applications include the generation of isotopes for use in nuclear medicine, and the production of high-tech materials for use in the semiconductor, nuclear, and other industries.

The SILEX process is also laser based. However, it is potentially a simpler and more energy efficient technology than AVLIS. The estimated total production costs for SILEX, including plant amortization, are $30 to $40 per SWU of enrichment.

Details of the SILEX process are not publicly available. However, SILEX is an MLIS process.

SILEX is a process in which lasers produce highly monochromatic radiation that can be primarily absorbed by only one of the uranium isotopes, leaving the other largely unaffected. The absorption of this

radiation causes physical or chemical changes to take place, modifying the target uranium isotope.

Utilizing novel engineering concepts, the modified species can then be easily separated from the unaffected isotopic species. The affected species become enriched in the desired isotope (called the product stream) while the unaffected species become depleted of that isotope (called the tails stream). In the case of uranium, this process is known as uranium enrichment, whereby the product stream becomes enriched in the uranium-235 isotope.

SILEX is still in the R&D stage. In November 1996, a license/development agreement was put into place for USEC to develop SILEX as an alternate new enrichment technology. A pilot module program to assess performance was completed in January 2000. This did not involve UF_6 testing.

The main application of the SILEX technology is the enrichment of uranium, a market which is estimated to have current worldwide sales of U.S. $3.5 billion annually.

Silex Systems Limited had an agreement with USEC, the largest participant in the industry, to further develop and potentially commercialize the SILEX technology for uranium enrichment.

On June 20, 2001, Silex Systems, Ltd. announced that its laser-based SILEX uranium enrichment technology (Separation of Isotopes by Laser Excitation) has been officially classified by both the U.S. and Australian governments. The new SILEX technology was being developed jointly by SILEX and USEC.

USEC discontinued its participation with SILEX in 2002, after making several progress payments, citing its focus on DOE gas centrifuges for new enrichment plants and the availability of LEU from HEU down bleeding programs. SILEX subsequently announced its tests were successful and supported attractive economies. Intergovernmental (U.S. – Australia) agreements on classification were concluded in 2006. In 2006, GE announced an exclusive agreement with SILEX to license the technology and develop the process commercially. GE has made payments to the SILEX company. GE is discussing licensing a SILEX test loop, and, subsequently, a commercial enrichment plant, with the NRC.

Other Countries

Brazil, Iran, South Korea, and a few other countries have tested LIS and produced enriched uranium at a laboratory scale (milligram and, in some cases, gram quantities). Assays have ranged from power reactor LEU to HEU (50% – 70%). As of this time, these programs have not progressed into larger facilities.

Self-Check Questions 3-5

Complete the following questions. Answers are located in the answer key section of the Trainee Guide.

1. Match the Enrichment Process (Column A) with the appropriate Country (Column B).

Enrichment Process Column A	Country Column B
_____ U-AVLIS	A. Australia
_____ RIMLIS	B. France
_____ SILEX	C. Japan
_____ SILVA	D. United States

2. What approach has SILEX developers pursued?

3. What are some typical enrichment levels achieved overseas by LIS?

You have completed this section.
Please check off your progress on the tracking form.
Go to the next section.

Learning Objective

When you finish this section, you will be able to:

3.1.6 Identify the hazards and safety concerns for the LIS processes, including major incidents.

LIS HAZARDS AND SAFETY CONCERNS

There are many health, safety, and physical safeguards associated with uranium enrichment. The various unit operations are performed in a safe and secure manner consistent with applicable state and federal regulations. UF_6 is a highly corrosive and reactive compound. Face masks and protective clothing are worn when handling UF_6 cylinders. Emergency breathing air is provided via portable bottles at strategic locations throughout the plant. All interconnected process piping, valves, pumps, and compressors must be free from moisture, oils, and lubricants to prevent exothermic reaction. All are purged with dry nitrogen after being exposed to the atmosphere.

Criticality is of the utmost safety concern in uranium enrichment plants. All process equipment containing UF_6 is safe from criticality by geometry or unmoderated. All process piping, valves, vessels, and pumps in the system that contain UF_6 are operated at subatmospheric pressures to permit inward leakage, if any.

The uranium enrichment facilities are provided with strict physical and institutional safeguards. The enrichment plants are surrounded with high steel fences to prevent intrusion and physical theft.

The plant entrances are equipped with security guards, X-ray equipment, and check points to prevent entry of unauthorized personnel. United States citizenship is mandatory for personnel working in uranium enrichment plants. Besides U.S. citizenship, plant operation and support personnel must have the appropriate level of DOE security clearance. The level of security clearance depends on the degree of classified information handled by the employee.

Conventional Hazards

Conventional hazards associated with the use of high-powered lasers (that is, high voltages and high-powered laser beams) are common to this method. For example, potential eye damage exists if workers are exposed to laser beams. In addition, the possible toxicity of laser dyes and potential fire/explosion hazards associated with high-pressure dye/solvent circuits should be taken into account during safety assessments. Dye lasers utilize a solution of an organic dye and ethanol under high pressure flowing through the laser system. Containment of high-temperature corrosive uranium vapor poses

some metallurgical problems. This will require the containment vessel to be designed to withstand/prevent any over pressurization resulting from contact of liquid uranium with cooling water.

The most serious potential health physics problem associated with this process is inadvertent exposure to the extremely high X-ray fields generated within the vacuum vessel. While the vessel walls provide complete shielding against these X-rays, any penetrations (for example, instrument feed-throughs) are potential problem areas.

Uranium hazards associated with this process are similar to those associated with uranium metals and uranium oxides. Table 3-2 identifies some of the hazards associated with the AVLIS enrichment process.

Table 3-2. LIS Hazards

Hazards	Hazard Descriptions
Chemical and Chemical Reaction Hazards	4. Alcohol 5. Ammonia - liquid and fumes 6. Ammonium diuranate 7. Ammonium nitrate 8. Compressed gases 9. Diesel and gasoline 10. Heavy metals 11. Hydrofluoric acid - liquid and fumes 12. Hydrogen gas (H_2) 13. Inert atmospheres 14. Lime solutions 15. Nitric acid 16. Nitric oxide (HNO_3) 17. Propane/natural gas 18. Technetium (Tc) 19. Uranium metal 20. Possible hazards exist if normal containment systems fail or are breached in some manner in the following systems: - Dye laser: ethanol/organic dye solution under high pressure reacting with air--fire, probable explosion hazard. - Separator containment vessel: fire with molten U/air, uncontrolled H_2 formed, probable explosion hazard when vaporized U reacts with air. - Sealed water cooling system for separation equipment: breach water line causes exothermic reaction with molten U. Steam pressure buildup results, could cause breach in separator containment. H_2 is also produced, causing explosion hazard if vessel is breached and O_2 enters separator.
Physical/ Mechanical Hazards	• Connecting/disconnecting sealed product and tails stream collection pots • Laser electrical exciter 40-kV range high power • Heat stress, lifting with cranes/hoists • High-energy system on laser beam, electron beam • High voltage on electrical beam power supply 10- to 100-kV range • Molten at 1200^{o}C and vaporized at 3400^{o}C, 10^{-6} TORR vacuum on separator vessels • Physically hot material

Table 3-2 LIS Hazards (Continued)

Hazards	Hazard Descriptions
Radiological/ Criticality Hazards	• Radiological hazards exist during maintenance because of the substantial amount of maintenance continually required refurbishing pods • Low-level alpha--respiratory hazard • Low-level gamma emissions • X-ray • In the separator, criticality is a hazard from loss of borated water. • At 3% to 4% assay, nuclear criticality hazards are of low probability because of geometrically safe containers used to collect product stream
Fire and Explosive Hazards	• Dye laser uses solutions of organic dye and solvent, high flammability and explosion potential • Explosion potential if breach in water-cooling system inside separator--reaction will form H_2
Environmental and Natural Disasters	• Normal seismic hazards, tornado, or flood could breach containment or cause misalignment of laser beam--release of energy

Environmental Concerns

The environmental concerns surrounding LIS are focused in four primary areas:

1. AVLIS would produce wastes for which no permanent disposal technologies exist. The wastes include large quantities of depleted uranium, liquid radioactive wastes, and mixed radioactive-hazardous wastes.

2. Neither DOE nor USEC has ever prepared an environmental impact statement (EIS) on the AVLIS program.

3. LIS poses a nuclear proliferation concern. A partially-classified 1979 DOE report concluded that AVLIS could pose verification problems if a foreign nation could overcome certain technical issues.

4. If conventional methods are used to make the uranium metal for feed, large quantities of magnesium fluoride, slightly contaminated with uranium, are produced.

Table 3-3 summarizes AVLIS hazards and dilemmas. Table 3-4 summarizes MLIS hazards and dilemmas.

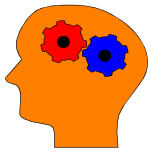
Table 3-3. Summary of AVLIS Hazards and Dilemmas

1.	Fuel cycle changes that add additional steps to produce uranium metal and then additional steps to convert the enriched and depleted uranium metal streams back into the oxides. Each fo these changes require facilities with ES&H concerns.
2.	AVLIS is a batch process. The separators/pods require frequent shutdowns for product/tail recovery, clean-out, and refurbishment.
3.	AVLIS has a vacuum contradiction. A high vacuum is needed for improved laser separation efficiencies while a low vacuum is needed for reasonable throughputs. Vacuum systems complicate operations and maintenance and introduce hazards.
4.	The separators/pods and collectors are complicated to design, fabricate, operate, and maintain.
5.	Main Environmental Safety and Health Concerns: – temperature extremes (hot and cold) – relatively high frequency of opening separators – high potential for uranium coatings and plateout in equipment – uranium metal pyrophoricity/sparking hazards – intimate high energy equipment, such as lasers and electron beams – x-ray radiation from electron beam interactions – liquid/gaseous uranium metal corrosivity and reactivity – dense phases, water, and criticality concerns – five hazards from lasers, dyes, and reactions producing hydrogen (uranium-water, uranium-water vapor) – unknown reliabilities–some industrial analogues have high failure rates
6.	Many IROFS likely needed
7.	Extra proliferation concerns due to the small size and high separation factors

Table 3-4. Summary of MLIS Hazards and Dilemmas

1.	MLIS processes are at the R&D stage and information is limited.
2.	ES&H issues have not been fully considered and addressed.
3.	MLIS is compatible with the existing U.S. fuel cycle because it uses UF_6, but this presents handling hazards.
4.	MLIS utilizes carrier gases and scavenging chemicals. These are asphyxiants and may be flammable.
5.	MLIS requires gas processing with phase changes and solids handling.
6.	Partially fluorinated species and gases may be generated including fluorocarbons.
7.	Industrial scale separators are likely to be complicated and multiple stages may be necessary.
8.	Cryogenic temperatures are usually needed.
9.	High energy equipment and lasers are used.
10.	LEU solids may accumulate and present criticality concerns.
11.	Equipment reliability and safety impacts are not well known.
12.	Extra proliferation concerns due to the small size and high separation factors.

Activity 3 - Hazards of the AVLIS Process



Purpose: The purpose of this activity is to review hazards associated with the AVLIS process.

Instructions: Complete the following activity. Answers are located in the answer key section of the Trainee Guide.

1. What is the most serious potential health physics problem associated with the AVLIS process?

2. If AVLIS containment systems fail, what two processes produce hydrogen gas?

3. Using the code provided, identify the hazard category for each hazard descriptions.

C = Chemical and Chemical Reaction Hazards
P = Physical /Mechanical Hazards
R = Radiological/Criticality Hazards
F = Fire and Explosive Hazards
E = Environmental and Natural Disasters

_____ Solutions of organic dye and solvent, high flammability and explosion potential

_____ Separator containment vessel

_____ Low-level alpha-respiratory hazard

_____ High-energy system on laser beam, electron beam

_____ Propane/natural gas

_____ Physically hot materials

_____ Normal seismic hazards, tornado, or flood

_____ Sealed water cooling system for separation equipment

_____ Low-level gamma emissions

_____ Hydrogen gas (H_2)

_____ Connecting/disconnecting sealed product and tails stream collection pots

_____ Hydrofluoric acid - liquid and fumes

_____ High voltage on electrical beam power supply 10- to 100-kV range

_____ Heat stress, lifting with cranes/hoists

_____ Explosion potential if breach in water-cooling system inside separator

_____ Diesel and gasoline

_____ Laser electrical exciter 40-kV range high power

_____ Alcohol

_____ Continued maintenance to refurbish pods

_____ Loss of borated water in the separator

Self-Check Questions 3-6

Complete the following questions. Answers are located in the answer key section of the Trainee Guide.

1. What are the common characteristics of uranium hexafluoride (UF_6)?

   a. UF_6 is a very stable compound.
   b. UF_6 is an unstable but nonreactive compound.
   c. UF_6 is a highly corrosive but mordant compound.
   d. UF_6 is a highly corrosive and reactive compound.

2. What are unique hazards of the AVLIS system?

   a. HF, UF_6
   b. lasers, UF_6
   c. lasers, X-rays
   d. X-rays, high-speed components

3. What protective clothing is worn by individuals handling UF_6 cylinders?

   a. Gloves only are needed.
   b. Respirators are mandatory.
   c. Protective clothing is unnecessary.
   d. Face masks and protective clothing are worn.

4. All interconnected process piping, valves, pumps, and compressors must be free from moisture, oils, and lubricants to prevent exothermic reaction. After being exposed to the atmosphere, what compound is used to purge them?

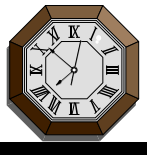
   a. Dry ice
   b. Dry nitrogen
   c. Lime solutions
   d. Compressed air

5. The most serious potential health physics problem associated with this process is inadvertent exposure to the extremely high _____ generated within the vacuum vessel.

   a. gamma rays
   b. X-ray fields
   c. concentration of nitric acid
   d. voltage on the electrical beam power supply

You have completed this section.
Please check off your progress on the tracking form.

It's time to schedule a progress meeting with your administrator. Review the progress meeting form on the next page. In Part III, As a Regulator, write your specific questions to discuss with the administrator.



Progress Review Meeting Form

Date Scheduled:_____ Location:_____

I. The following suggested items should be discussed with the administrator as to how they pertain to your current position:

- Principle of the AVLIS process
- AVLIS components
- Industrial use of the AVLIS process
- AVLIS hazards and safety concerns

II. Use the space below to take notes during your meeting.

III. As a Regulator:

What documentation on AVLIS or any other laser technology would you like me to review?

Use the space below to write your specific questions.

IV. Further assignments? If yes, please note and complete. If no, initial completion of progress meeting on tracking form.

Ensure that you and your administrator have dated and initialed your progress on your tracking form for this module. Go to the module summary.

MODULE SUMMARY

LIS processes use laser light sources to exploit small electron energy differences between isotopes and, thus, enrich uranium. The electron energy differences are very small but, with precision lasers, the stage separation factors can be very large. There are two basic LIS processes: atomic (AVLIS), which uses uranium atoms as a vapor, and molecular (MLIS), which uses a uranium compound, such as UF_6. AVLIS uses finely tuned lasers to ionize and recover one isotope (usually U-235). MLIS uses finely tuned lasers to change molecular bond energies and electrons, thus forming a new compound enriched in one of the energies. Uranium LIS processes have produced both LEU and HEU in laboratory experiments; in the case of AVLIS, kilogram quantities of LEU have been produced and power reactor LEU levels achieved in one stage.

Potential advantages of LIS include a high separation factor per stage, low energy consumption, small plant size, and improved economics as compared to other existing enrichment technologies. However, scale-up has proved to be difficult as both AVLIS and MLIS require solutions to engineering issues, many of which involve trade-offs between efficiencies and production rates. In addition, ES&H issues have not been fully determined and vetted so far.

Many countries have pursued some form of LIS research and/or development, including the U.S., France, Japan, Australia, Brazil, South Korea, and Iran. The U.S. had an extensive, multi-year R&D program on AVLIS with a total cost exceeding $2 Billion. USEC planned to use AVLIS for a new enrichment facility in the late 1990s and initiated licensing discussions with the NRC. However, USEC canceled its program because of concerns about timing (for additional R&D and market demand), reliability, and economics. Worldwide LIS activities have also declined in the past few years.

At the present time, an MLIS process called SILEX is the only LIS program with significant activity. GE has licensed the SILEX process and announced plans to test, demonstrate, and deploy the technology. Pre-licensing discussions have been initiated with the NRC.

Congratulations! You are ready to go to the next assigned module.