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Enrichment Separative Capacity for SILEX

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Introduction

The objective of this study is to provide guidelines for estimating the isotope enrichment separative capacity for the technology known as SILEX.

Separation of **I**sotopes by **L**aser **EX**citation (SILEX) is the name given to the technology developed by Australian scientists, Michael Goldsworthy and Horst Struve. They formed a public company, Silex Systems Ltd. (SSL), to further develop and market the isotope enrichment capability for uranium and several stable isotopes. Their current facilities are in Australia at Lucas Heights, New South Wales. The facilities are in a secure area in a building rented from the Australian Nuclear Science and Technology Organization (ANSTO). ANSTO provides security and other services for the SSL. Michael Goldsworthy is the CEO of SSL and Horst Struve is the Chief Scientist.

From 1996 to 2002 the United States Enrichment Corporation (USEC) provided funding and technical assistance to SSL for their uranium enrichment process. I was part of that technical assistance from 2000 to 2002. My understanding of the process allows me to make the guidelines presented here. USEC no longer has an interest in the SILEX technology. All contractual arrangements between SSL and USEC have been terminated. I understand, however, that SSL is pursuing agreements with other US companies. The SSL objective is to build a uranium enrichment pilot plant in the United States. I also understand that SSL has no interest in marketing the technology outside of the United States. I know of no organization outside of the United States that has an interest in developing the SILEX technology. Even Australia cannot build a pilot plant or enrichment facility.

During the time of the USEC-SSL cooperative research the United States and Australian governments concluded an "Agreement for Cooperation [1]" that allowed joint research on uranium isotope separation to take place. It also provided a basis for the classification of the work by both the Australian government and the United States Department of Energy. Many aspects of the uranium enrichment technology are also company proprietary. As many aspects of the SILEX process are covered by Australian and American classification and the proprietary restrictions, many details of the SILEX process cannot by revealed in this report.

In addition to the time I worked for USEC with SSL in Australia, I also wrote the review of the SILEX process for the International Atomic Energy Agency (IAEA) in February 2005[2]. The report discusses a visit of three IAEA representatives and myself to SSL to assess the potential for the company (SSL) to produce significant quantities of highly enriched uranium (HEU). That report is classified "Safeguards-in-Confidence" by the IAEA and is not available for distribution beyond the Agency. The report did conclude that SSL is not currently capable of producing significant amounts HEU. I use some the same techniques as used for the report in this document to establish the guidelines.

Description of the SILEX methodology

SSL has several corporate objectives. The one that is of interest to us is to develop a method for uranium enrichment for nuclear fuel for electric power generation.

Because the process involves proprietary information and is classified by the two governments, this description will be incomplete. The description in the Physical Model[3] is also incomplete. It contains only one short paragraph that says that little is known about the process. Another document[4] is also available that describes the process, but is classified and has restricted distribution.

The process uses a mixture of UF_6 with a carrier gas. The gas mixture is cooled to separate the resonance peaks for the two isotopes (^{235}U and ^{238}U). A 16-*μm* laser then selectively excites the $^{235}UF_6$. One or more infrared laser frequencies may be used. The laser excitation results in a separation into a product stream and a tails stream. The product stream is enriched in ^{235}U while the tails stream has an increased fraction of ^{238}U. In a plant situation the two streams would be further processed to achieve the desired enrichment and physical form. In the research laboratory in the current SSL facility the two streams are combined, remixed with the carrier gas, and returned to the feed tank.

The main SSL experimental facility is the Direct Measurement (DM) laboratory. It consists of:

1. A large process vessel where the separation occurs,
2. A feed vessel that contains the UF_6 and carrier gas mixture,
3. Vessels for containing the product and tails,
4. A quadrupole mass spectrometer for measuring the isotope ratios in the feed, product and tails streams,
5. The necessary plumbing and processing facilities for carrying out the experimental tests, and
6. All necessary optics for bringing the laser radiation to the process vessel.

Pulsed laser radiation at a specific16-*μm* wavelength is necessary to achieve the isotope enrichment. The lasers are in an adjacent room and the laser radiation is brought through a port in the wall to the process vessel. The laser radiation for the process begins with one of several pulsed CO_2 lasers. These are capable of producing laser pulses at a 300 Hz repetition rate. The lasers are capable of producing one joule pulses, but not at high repetition rate. The fact that the lasers must be at a specific frequency further reduces the energy per pulse. The laser pulses in the 10.8-μm region are taken to a Raman conversion cell where they are converted to the 16-*μm* region. The Raman cell is a large vessel filled with high-pressure *para*-hydrogen. The 10.8-μm laser radiation is passed through the Raman cell many times (~25), and on each pass it goes through a focus near the center of the cell. The result is a nonlinear optical process that reduces the laser photon energy by a quantum of *para*-hydrogen rotational energy to produce the desired 16-*μm* laser radiation. To obtain the exact laser frequency it is necessary to use some additional nonlinear optical tricks on the initial CO_2 laser pulse and to operate the laser at high pressure.

Guidelines for assessing separative capacity

Feed and product materials

The feed for a hypothetical isotope enrichment plant based on the SILEX technology is uranium hexafluoride (UF_6). It is really the only possible uranium feed material. All other uranium-bearing species have insufficient volatility to be used in the process, and the process must occur in the gas phase.

The amount of UF_6 required to produce a significant amount of HEU is substantial. As an example, assume the plant produces 10 kg of 85% U-235 and that process is sufficiently selective to take natural UF_6 from 0.721% to 0.221% $^{235}UF_6$ in the tails stream. This requires 2500 kg of natural UF_6 feed.

A carrier gas to dilute the UF_6 is necessary for the process to enrich uranium. The amount of the carrier gas is substantially greater than the UF_6 during the isotope separation process. It, however, is not consumed and can be separated and reused. The identity of the carrier gas and the dilution fraction are protected by the classification and proprietary restrictions.

The nature of the product stream is again covered by the proprietary restrictions, but we do know that the processing takes considerable time, at least under the current experimental conditions. SSL has stated that an experimental run in their current facility requires ten hours for preparation, about an hour for the run to occur, and another ten hours to get everything ready for the next run. This preparation and processing time is a significant restriction on the amount of enriched material produced.

Material processing

The current SSL research facility uses infrared lasers that operate at 50 Hz. The nature of the enrichment process is that a considerably higher repletion rate would be necessary to process a large fraction of the feed material. The 50 Hz laser system only allows a 1% duty factor. That is, 99% of the feed material is unprocessed. This results in a high fraction of the feed material getting into the product stream. Consequently, the observed enrichments are low. A working enrichment plant would require large improvements in the laser repetition rate.

Equipment signatures

The lasers themselves are a significant indication of the maturity of the process and the capability to produce significant enrichment. We noted that a 50 Hz repetition rate is not sufficient. A mature facility would have the capability to increase that rate by more than an order of magnitude. The pulse energy of the CO_2 laser also needs to be in the 1 J range. It is not just that the rate needs to be high for high production. At low rates the process does not work because of large amounts of unprocessed material in the product stream.

The Raman converters are essential and at the projected high repletion rates considerable attention needs to be paid to the problem of energy deposition in the *para*-hydrogen converting gas. This heating can produce optical interference that obscures or deflects later laser pulses. The Raman converters must be well engineered with facilities to flow the hydrogen gas.

Restrictive potential of irradiated volume

One feature of the physical arrangement of the laser processing provides a limit on the amount of material that can be processed. It is the volume irradiated per pulse. It provides a better restriction on the enrichment capacity than the electrical power consumption or the laser output power. Although we can give no indication of the process of enrichment, we can conclude that the process is similar to other MLIS enrichment technologies. That is, it requires vapor phase irradiation at low temperature with the infrared lasers. We know from those processes that rapid, catastrophic condensation occurs if the UF_6 molecular density gets to high. I know from experience with many molecular laser enrichment programs that the molecular density cannot exceed 1×10^{15} *molecules/cm*^{3}. Given that density, irradiated volume, the laser repletion rate, and the natural abundance of ^{235}U, we can calculate the amount of time to process some quantity, say 1.0 *kg* of ^{235}U. For a 1.0 *l* irradiated volume and a natural abundance of 0.721% ^{235}U we find that it takes 12 eight-hour days to process the 1.0 *kg* of ^{235}U. This calculation ignores that fact that the laser process is not perfect and multiple stages will probably be required. It does, however, give a generous upper limit on the enrichment capacity. One can estimate the irradiated volume from the physical length of the process vessel and the diameter of the input beam.

Utilities requirements for production

For a plant that is using the SILEX technology to enrich uranium the main utility requirement is electrical power for operating the lasers. Significant electrical power would also be necessary for maintaining vacuum conditions in the process vessel, for pumping the process gas, and separating the components.

We can make an assessment of the electrical power required for the operation of the lasers. The CO_2 lasers themselves are about 1% efficient. The conversion to 16-μm laser radiation is about 25% efficient. The laser power required for tests in the current SSL experimental facility is 12 W. This would need to be enhanced by at least a factor of twenty to obtain high enrichment. By considering all of these factors we obtain an electrical requirement of about 100 kW for the lasers for a single process vessel. This would be the minimum power requirement for processing the 1.0 *kg* of ^{235}U in eight days mentioned in the previous paragraph.

Potential separative capacity from number and type of units

The previous paragraphs irradiation volume and electrical power requirements for a single process vessel indicates what a single unit is capable of achieving in the hypothetical SILEX enrichment facility. Because of difficulties with laser transport, it would be difficult to have larger separation units the test facility currently being used by SSL in Australia. The value given above of 12 days to process 1.0 kg of ^{235}U is an upper limit. As we can say nothing about process efficiency or enrichment factor, we just make the note that any inefficiency will increase the amount of time required to process 1.0 kg of ^{235}U.

Evaluation of workforce

We address here the question of what the characteristics of the workforce tells us about whether a particular facility is devoted to R & D or isotope production. The necessary expertise for running a production facility has some common features with the expertise required for R & D. Both will require someone with the capability to operate complex laser systems. Since a production facility will not require the development of methods of doing such things as changing the laser frequency, a complete knowledge of laser physics and quantum optics would be unnecessary. Good technicians with the capability to operate (and repair) existing laser facilities would suffice. Because the production facility would run for long periods of time and because the processes need to be continuously monitored, the production facility would require several people with this capability. Personnel with the skills of optical technicians would be necessary in a production facility. These are people who not only could operate and repair lasers, but could facilitate the transport and control of the laser radiation.

Likewise, it would be unnecessary for the production facility to have on the staff people who understand the physical processes that occur during and after the interaction of the laser radiation with the feed gas. These processes should have been investigated and understood during the R & D phase of the project.

One production facility requirement would be workers that would handle the product and tails streams. Someone would need to be able to make whatever chemical and physical changes are necessary to the product stream and to prepare the material for additional stages of processing. Again, this does not require a high level of scientific education and expertise. It does require sufficient technical training to effectively carry out the necessary operations.

Guidelines on personnel for processes that go beyond R & D

Information in open sources should be available for determining the education and skill level of personnel in different countries that could be used in a SILEX type isotope production facility. Some the people most likely to be involved would include optical technicians who could operate, repair, and control infrared lasers and the laser radiation they produce. The optical elements such as salt windows, infrared reflecting mirrors, and focusing optics require specially trained personnel. The handling of uranium hexafluoride requires some special skills that few people have. It is a volatile solid that has its own chemical and radiation hazards. People trained in radiation and chemical hazard safety need to be part of any production facility.

Recommendations for inspectors

The first recommendation is that inspectors take environmental swipes to be analyzed later for the presence of uranium, particularly for uranium fluorides such as UO_2F_2. This material is produced by reaction of UF_6 with ambient water. The uranium isotope ratios should be measured. If the isotope ratio is not natural it indicates one of two things. Either the facility could be producing enriched uranium or the researchers had obtained enriched uranium for R & D purposes. As the natural fraction of ^{235}U is so low, it is extremely difficult to develop an isotope separation process with only natural uranium. Enriched uranium is almost a necessity in R & D.

Radiation detectors that could detect the presence of uranium are essential unless the facility is known to have uranium present.

If the SILEX process is being used, lasers will be present. They are noisy. A high repetition rate laser issues a loud hum. They are easy to hear when they are operating. Another indication of the presence of lasers is laser beam transport facilities. These can be in tubes or through open ports in room walls.

Raman converters are fairly large. They require in excess of a meter length with a diameter near a half-meter. They will also have optical ports and controls. The Raman converters also require access to high-pressure hydrogen with the capability to cool them with something like liquid nitrogen.

Laser goggles for eye protection will be present in the laser room and where the laser radiation is present.

The process vessel itself requires a great deal of plumbing with pipes and tubes for transport of the feed gas mixtures. They will also require large tanks for storage and mixing of the feed gas. The product and tails stream must also be handled similarly.

<u>References</u>

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4. Edward D. Arthur, Jeffrey J. Bedell, Harry J. Dewey, John L. Lyman, Anne Menefee, and Ernest J. Moniz, *Uranium Enrichment Technologies: Materials from a Los Alamos Workshop*, LA-CP-03-0233, March 30, 2003.