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Laser and Gas Centrifuge Enrichment

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Abstract. Principles of uranium isotope enrichment using various laser and gas centrifuge techniques are briefly discussed. Examples on production of high enriched uranium are given. Concerns regarding the possibility of using low end technologies to produce weapons grade uranium are explained. Based on current assessments commercial enrichment services are able to cover the global needs of enriched uranium in the foreseeable future.

INTRODUCTION

Commercial uranium enrichment companies are currently operating in China (China National Nuclear Corporation, CNNC), France (AREVA). Germany (URENCO), the Netherlands (URENCO), the Russian Federation (ROSATOM), the United Kingdom (URENCO), and USA (USEC and URENCO). These enterprises have a total annual enrichment capacity of 65 million separative work units (SWU)[1], which is well above the annual demand of about 45 million SWU. In addition, smaller enrichment facilities exist in Argentina, Brazil, India, the Islamic Republic of Iran, Japan and Pakistan.

There are several uranium enrichment methods (See Annex 1), but only gas diffusion, gas centrifuges, and SILEX are of relevance on commercial scale. The world's oldest operating enrichment plant - the Paducah gaseous diffusion plant in the United States ended its commercial operation in 2013. But new gas centrifuge enrichment plants will be built or current ones expanded. At the same time, the Global Laser Enrichment Facility (GLE) in Wilmington using laser enrichment technology is approaching its commercialization phase. With the onset of new gas centrifuge enrichment capacities, the World Nuclear Association expects that there will be in 2020 87 million SWU available to satisfy the estimated need of 60 million SWU[2]. Most of the world's enriched uranium will be produced by AREVA, CNNC, GLE, ROSATOM, and URENCO. In the light of these developments, there should be fairly little economical or security reasons for another country or commercial entity to embark on large enrichment projects elsewhere.

PROLIFERATION CONCERNS OF GAS CENTRIFUGE ENRICHMENT

Proliferation concerns arise from the dual use nature of uranium enrichment. The same centrifuges (and also laser enrichment equipment) can be used to produce – with fairly straightforward modifications - weapons grade (normally enriched to higher than 90 % U-235) uranium in place of low enriched uranium. From the safeguards point of view, there are three basic diversion strategies to accomplish this: diversion from declared enriched uranium inventory; unreported production of excess low enriched uranium; or of high enriched uranium. In the first two cases, uranium has to be transported to a clandestine facility to be further enriched to weapons grade. The basic IAEA verification scheme that was established in the early 1980's (so called Hexapartite Safeguards Approach) had various shortcomings that was inadequate in addressing such diversion attempts. The Agency's safeguards strategies were however further developed over time when the enrichment plants and throughputs grew larger, and

[1] SWU is used to measure to indicate effort required to produce desired amount of enriched uranium taking into consideration U-235 concentration in the feed, product, and tails. For the calculations, see reference 4 below.
[2] http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Conversion-Enrichment-and-Fabrication/Uranium-Enrichment/

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when the cascades designs became more flexible. The current IAEA verification approach includes process monitoring, announced and unannounced inspections to cover all three diversion scenarios mentioned above[3].

The IAEA has established a significant quantity (SQ), which is a defined amount required by a rogue state to produce enough nuclear material for first nuclear device. One SQ is 25 kg U-235 or approximately 28 kg weapons grade uranium. It takes 5000-5500 SWU to produce one SQ of weapons grade uranium from natural uranium feed. As an example, using a German G-2 centrifuge which has a capacity is ca 5 SWU/year[4], about one thousand such centrifuges are required to produce a significant quantity from natural uranium in one year's time. With 2000 such centrifuges, it would take half a year; and with 4000 thousand centrifuges, about 3 months. As shown in Figure 1, the time required to produce one significant quantity using enriched uranium as a feed is much shorter. If one uses typical light water reactor fuel product as a feed, more than half of the enrichment effort required to produce weapons grade material is already accomplished. If the feed is a typical research reactor fuel material, ca 20 % U-235, 90 % effort required is already accomplished. With 4000 G-2 centrifuges, it would take about one and half months to produce enough material for a single nuclear device from 4-5 % feed. If the feed is 20% enriched uranium, a couple of weeks is enough to produce material for a single nuclear device.

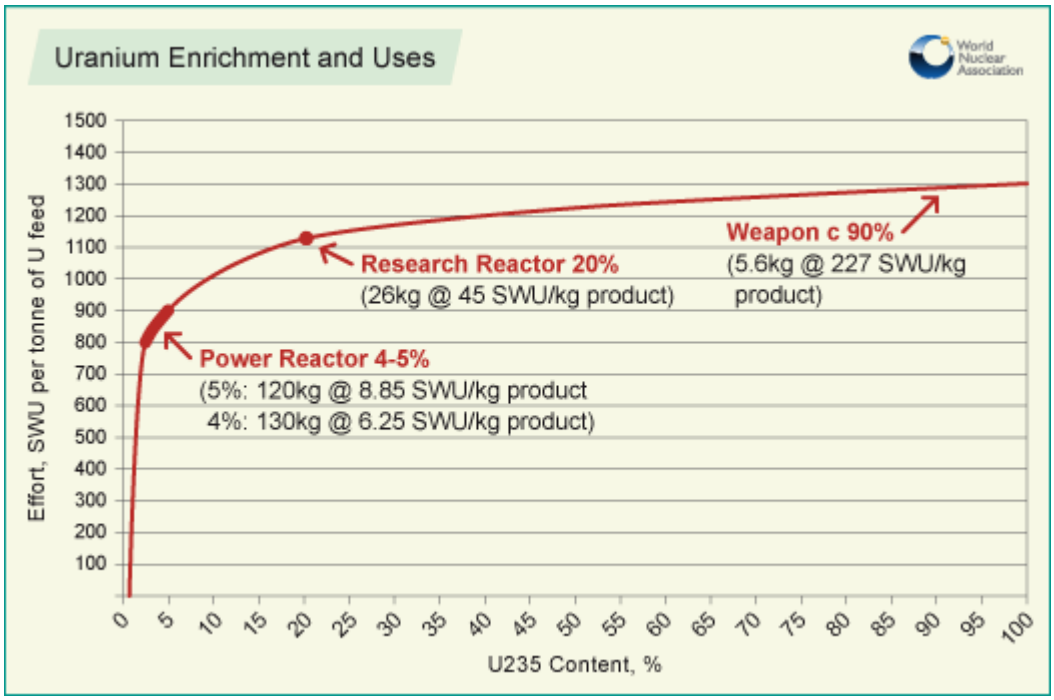

FIGURE 1. Effort to produce enriched uranium from natural uranium feed. Source: World Nuclear Association.

G-2 centrifuges were developed in 1960s-1970s, but modern centrifuges such as Russian, URENCO TC12 or TC21, or American centrifuges have separative powers of 4-8, 40-45 or 80, or 350 SWU/year per machine, respectively. The first generation Iranian centrifuge, IR-1, which is based the old Dutch SNOR/CNOR design obtained through A. Q. Khan (Pakistan) has, according to the IAEA reports, a capacity of slightly less than 1 SWU/year machine[5]. This lower than expected performance – it should be 2-3 SWU/year per machine – could be a combination of design and manufacturing problems, and lower grade raw materials used in the production of centrifuges. However, Iran has produced with IR-1 centrifuges since 2007 more than 11 tons UF6 enriched up to 5 % U-235, and 450 kg UF6 with 20 % U-235. If these are further enriched to weapons grade uranium, the amount is sufficient for half a dozen nuclear devices. With the IR-1 centrifuges available in Natanz and Fordow in February 2014, weapons grade material enough for a first nuclear device can be produced in two months time.

[3] B. Boyer, H. Erpenbeck, K. Miller, K.Ianakiev, B. Reimold, S. Ward, J.Howell, Centrifuge Enrichment Plants Inspection Frequency and Remote Monitoring , LA-UR 10-06169, November 2010.

[4] Alexander Glaser, Characteristics of the Gas Centrifuge for Uranium Enrichment and Their Relevance for Nuclear Weapon Proliferation (corrected), Science and Global Security, 16:1–25, 2008.

[5] David Albright, Christina Walrond, and Andrea Stricker , ISIS Analysis of IAEA Iran Safeguards Report, ISIS, 20 February 2014.

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The example of Iran demonstrates that a state can achieve a status of a nuclear threshold state from the enrichment capacity perspective with fairly low technology - 1970's vintage - centrifuges. Such a program can also, as shown in the case of Iran and proliferation cases elsewhere, rely much on indigenous manufacturing capabilities with minimum import on special raw materials such as maraging steel or high strength aluminum. To quote A. Q. Khan himself: *"We devised a strategy by which we could go all out to buy everything that we needed in the open market to lay the foundation of a good infrastructure and would then switch over to indigenous production as and when we had to do. My long stay in Europe and intimate knowledge of various countries and their manufacturing firms was an asset."*[6]

LASER ENRICHMENT

It appears that from the laser-based processes (See Annex 2) only the SILEX method of GLE would be utilized on a commercial scale. There is a lively debate going on as to whether the development and deployment of laser enrichment technology presents an undue proliferation risk of enrichment technology[7]. GLE proponents assert that its laser enrichment secrets are well protected and the technical and financial barriers of laser enrichment technology make its spread unlikely. On the other hand, opponents point out that the laser process require less physical space and use less power, and add to proliferation concerns that such a technology renders a secret facility less detectable to the outside world, compared to similar 'traditional' centrifuge enrichment plants. Yet, while this is an internal debate taking place within the United States with attention to global ramifications, as the proliferation cases in Iran and South Korea have shown, the genie - the basic know-how on laser enrichment - is already in public domain. A good example of it is a literature study made by the Iranian laser scientists.[8] The Iranian case also demonstrates that after acquisition of basic AVLIS technology from foreign sources, one can proceed indigenously with the production of lasers, noting that Iran has an extensive laser R&D base.

Laser installations have a fairly small footprint, and no "tell tale" indicators, which can be observed e.g. from the satellite imagery. However, it is demanding to develop AVLIS to a continuous process since the feed material is uranium metal, and the collectors have to be also removed from a vacuum separation vessel. Due to the nature of the process, quite a lot of uranium remain in liners. While in the middle of the collectors material is weapons grade, also lower enrichments are trapped in collectors, which reduces the actual yield making the AVLIS less attractive compared to gas centrifuge process.

SUMMARY

Commercial enrichment services are able to cover the needs of enriched uranium in the foreseeable future. Gas centrifuges are dominating enrichment technology. The SILEX process may cover a small percentage of enrichment services during the coming decade. Overall, however, there is little commercial justifications to develop additional enrichment capacity beyond the planned capacity extensions of the current six service provides,

Both gas centrifuge and laser enrichment processes can be changed with minor modifications in a relative short time to produce weapons grade uranium. Fundamentals of both technologies are available in the open literature. Manufacturing of centrifuge rotors requires maraging steel, carbon fiber and or high strength aluminum, which are subject strict export controls. One can, however, sacrifice the speed of rotors and accept lower performance, which makes it possible to make rotors from materials of lower quality. Thus, with expanding the knowledge on material sciences and access to modern machine tools, such low technology centrifuges are within a reach of increasing number of states.

[6] Z. Malik, Dr. Khan and the Islamic Bomb, Hurmat, Islamabad, pp 93-94,1992.

[7] Elaine M. Grossman, Closely Held Report Discounts Proliferation Risk of Lasers for Making Nuclear Fuel, Global Security Newswire, 24 May 2012.

[8] P. Parvint, B. Sajad ,K. Silakhori, M. Hooshvar, and Z. Zamanipour, Molecular Laser Isotope Separation versus Atomic Vapor Laser Isotope Separation, Progress in Nuclear Energy,Vol.44,No.4,pp.331-345,2004.

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ANNEX 1. URANIUM ENRICHMENT PROCESSES

Diffusion techniques

- *Gaseous diffusion*[9] *(See Annex 3)*
- *Thermal diffusion*[10]

Laser techniques *(See Annex 2)*

- *Atomic vapor laser isotope separation (AVLIS)*
- *Molecular laser isotope separation (MLIS)*
- *Separation of Isotopes by Laser Excitation (SILEX*

Other techniques

- *Aerodynamic processes (South African nuclear weapons program)*[11]
- *Electromagnetic isotope separation*[12]
- *Chemical methods*[13]
- *Plasma separation*[14]

ANNEX 2: LASER ENRICHMENT

The mass difference between isotopes of a same element results in slight variations in the properties of the electronic clouds, which provides the possibility to excite U-235 selectively from other uranium isotopes. Using lasers to excite atoms or molecules of U-235 is the first step in the laser induced isotope separation process. The next step is then extract and collect the U-235 atoms or molecules. There are three laser processes, which have been developed beyond laboratory scale experiments: Atomic vapor laser isotope separation (AVLIS), Molecular laser isotope separation (MLIS), and Separation of Isotopes by Laser Excitation (SILEX). The only process reaching industrial scale operations is SILEX.

Atomic vapor laser isotope separation (AVLIS)

In the AVLIS process, uranium metal atom is selectively ionized with a laser beam. Traditionally tunable copper vapor lasers (CVL) were used produce the selective wavelength to excite U-235 atoms, which were then collected to a target as shown below.

Iran admitted (in 2003) and South Korea[15] (in 2004) that they had conducted uranium enrichment experiments without meeting their reporting obligations to the IAEA under their comprehensive safeguards agreements.

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[9] Henry De Wolf Smyth, Atomic Energy for Military Purposes, The Official Report on the Development of the Atomic Bomb Under the Auspices of the United States Government, Chapter X. The Separation of the Uranium, Isotopes by Gaseous Diffusion, http://www.atomicarchive.com/Docs/SmythReport/smyth_x.shtml.

[10] The Manhattan Project: Making the Atomic Bomb, Part II: Early Government Support, Liquid Thermal Diffusion, http://www.atomicarchive.com/History/mp/p2s6.shtml.

[11] J. M. Whitaker, Uranium Enrichment Plant Characteristics, A Training Manual for the IAEA, ORNL/TM-2005/43, May 2005.

[12] Henry De Wolf Smyth , Atomic Energy for Military Purposes, The Official Report on the Development of the Atomic Bomb Under the Auspices of the United States Government, Chapter XI. Electromagnetic Separation of Uranium Isotopes, http://www.atomicarchive.com/Docs/SmythReport/smyth_xi.shtml

[13] M. Seko, and K. Takeda, Separation of Uranium Isotopes by the Chemical Exchange Method, Separation Science and Technology, 28(1-3), pp. 487-505,1993.

[14] J. M. Whitaker, Uranium Enrichment Plant Characteristics, A Training Manual for the IAEA, ORNL/TM-2005/43, May 2005.

[15] J. Kang, P. Hayes, L. Bin, T. Suzuki and R. Tanter, South Korea's Nuclear Surprise, Bulletin of the Atomic Scientists, (Vol. 61, no. 01), January/February 2005, pp. 40-49.

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AVLIS

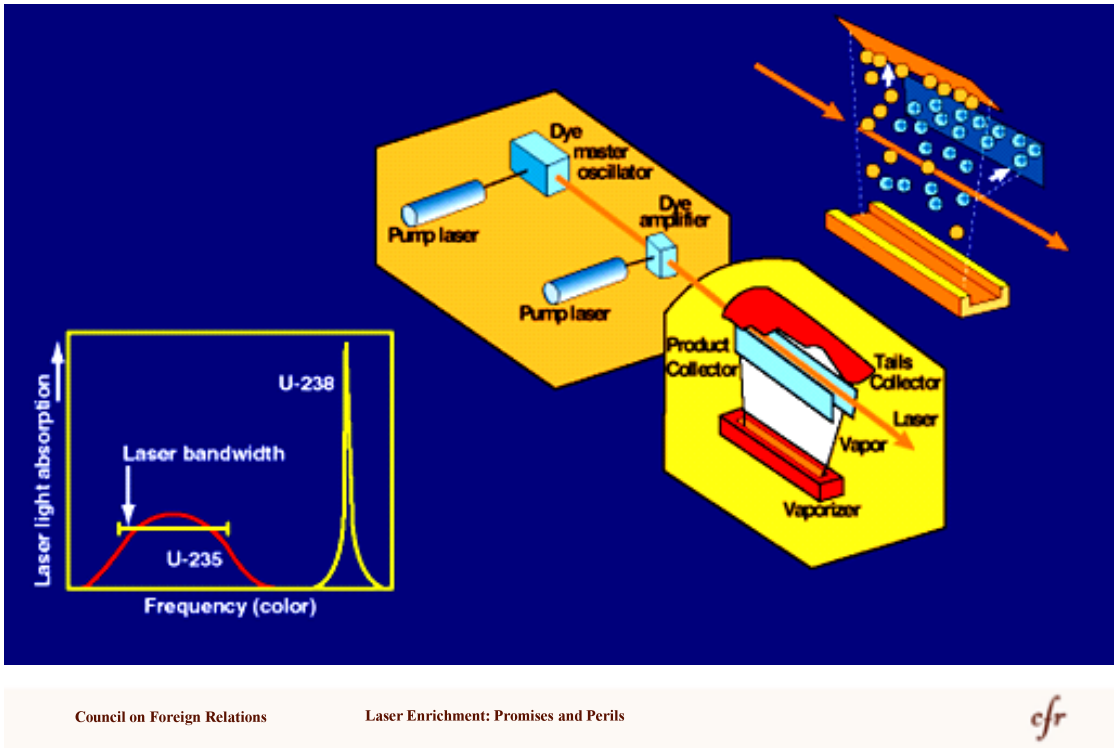

FIGURE 2. AVLIS system. Source: Council of Foreign Relations.

Molecular laser isotope separation (MLIS)

In the MLIS process uranium hexafluoride molecule with U-235 is first selectively excited by an infra red laser and the dissociated by another laser (infra red or ultraviolet laser). The resulted uranium penta fluoride (UF5) precipitates while the feed and tail materials remain as a UF6 gas. MLIS was developed in the 1970 to 1990 period. While the first step of providing selective molecular laser excitation was technically straightforward, the second MLIS step of "harvesting" excited isotopic species from unexcited ones, proved to be more difficult[16]. Thus the method has not proceeded to industrial scale.

Separation of Isotopes by Laser Excitation (SILEX)

Details of the SILEX process are classified, but the excitation mechanism is known to be similar to MLIS, where U-235 is selectively excited. In this process, UF6 is fed to the separation cell with a carrier gas[17], which is cooled to achieve sufficient separation for the resonance peaks of uranium isotopes. The system uses CO2 infrared lasers, which are converted to the desired 16 micrometer wavelength in a Raman cell. In this process, feed, product, and tails remains as UF6, and the carrier gas, which specifics are proprietary information, is recycled.

[16] J. W. Eerkens, J. F. Kunze , and L. Bond, Laser Isotope Enrichment for Medical and Industrial Applications, 14th International Conference on Nuclear Engineering, ICONE 14, ,July 2006
[17] J.L. Lyman, Enrichment Separative Capacity for SILEX, LA-UR-05-3786.

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ANNEX 3: GAS CENTRIFUGE ENRICHMENT

The idea of using centrifuges for uranium enrichment was also considered by the Manhattan project, which the opted for the gaseous diffusion and electromagnetic separation of uranium isotopes. The Soviet nuclear program, with participation from its war prisoners including Gernot Zippe, selected this route parallel to its gaseous diffusion for uranium enrichment. Since then a number of nuclear programs – civilian and non-civilian – devoted efforts to uranium enrichment using centrifuges, but China, Germany, Russia, the United Kingdom, USA. Japan, Pakistan, Iran, and Brazil have reached industrial capacity.

A gas centrifuge process is based on the principle where UF6 gas is introduced into the center of a fast rotating rotor. Due to the centrifugal forces the heavier molecules (U-238) move towards the wall, and the lighter ones (U-235) remain closer to the center of the rotor. In addition, by creation of a thermal gradient, where the top of the rotor is kept cool and the lower part hot, one can get the lighter molecules (U-235) to move towards the top of the rotor. One can then with the scoops, extract the heavier (tail) and lighter fractions (product) of gas from the rotor. However, the separation factor – the ratio between the product/tails - in such a rotor is very small. Thus the centrifuges are connected to a series, a cascade, to produce desired enrichment.

Much of design information on centrifuges can be found in open literature[18]. Such information has also been proliferated by for employees or sub-contractors of technology holders as the cases of Iraq, Pakistan, India, Iran, and Libya demonstrate.

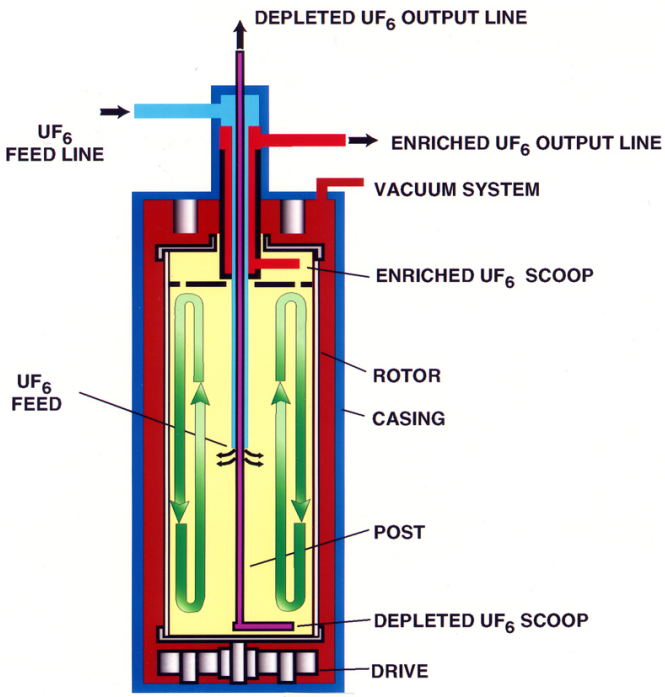

FIGURE 3. Gas centrifuge. Source: U.S. Department of Energy.

Centrifuges are spinning with high speeds – the wall velocities of the rotors are 400-800 m/s – requiring well balanced rotors and high strength construction materials. Rotating components of rotors are made of maraging steel, carbon fiber and or high strength aluminum, which are subject strict export controls. One can, however, sacrifice the speed of rotors and accept lower performance, which makes it possible to make rotors from materials of lower quality. Thus, with expanding knowledge on material sciences and access to modern machine tools, such low technology centrifuges are within a reach of increasing number of states.

[18] S. A. Levin, D.E. Hatch, and E. von Halle, Production of Enriched Uranium for Nuclear Weapons by Nations X, Y, and Z by Means of the Gas Centrifuge Process, Report KOA-662, Union Carbide Nuclear Company, 26 February 1960.

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