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Uranium Enrichment

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CONTENTS

8.1	History of Uranium Enrichment	265
8.1.1	Beginning.....	265
8.1.2	Evolution of Uranium Enrichment.....	266
8.2	What is Uranium Enrichment?	266
8.2.1	Grades of Enrichment	267
8.2.2	Separative Work Unit (SWU).....	267
8.3	Methods of Uranium Enrichment.....	267
8.3.1	Thermal Diffusion	267
8.3.2	Electromagnetic Isotope Separation	267
8.3.3	Gaseous Diffusion	268
8.3.3.1	Background of Gaseous Diffusion	268
8.3.3.2	Gaseous Diffusion Process	270
8.3.4	Gas Centrifuge	272
8.3.4.1	Background of Gas Centrifuge Enrichment.....	272
8.3.4.2	Gas Centrifuge Process	273
8.3.5	Laser Isotope Separation.....	275
8.3.5.1	Laser Isotope Background	275
8.3.5.2	Laser Separation Processes.....	277
8.3.6	Plasma Separation.....	278
8.3.7	Aerodynamic Processes.....	278
8.3.8	Chemical Exchange	278

8.1 History of Uranium Enrichment

8.1.1 Beginning

Physicists all over the world were excited by the announcement in January 1939 by the German chemists Otto Hahn and Fritz Strassman that the nucleus of the uranium atom produced barium when bombarded with neutrons. It was deduced by Otto Frisch and Lise Meitner that the barium resulted from the splitting or fissioning of the uranium

nucleus. The German work was quickly confirmed by four laboratories in the United States (Columbia University, Carnegie Institute of Washington, Johns Hopkins University, University of California) and others around the world. Those well recognized for their work at that time were Niels Bohr and E. Fermi. The possible military applications of "atomic power" were soon being discussed in every country. In the United States, studies of the possible approaches and problems were undertaken with government support in 1940. These studies produced promising results and culminated in June 1942 with the decision by the government to undertake an all-out effort to develop the bomb.

During the next six months, the Manhattan Engineering District of the U.S. Corps of Engineers was organized to direct the work. Two routes were undertaken: the uranium route at Oak Ridge, Tennessee in new facilities (code-named Y-12 and K-25); and the plutonium route in new facilities in Oak Ridge (code-named X-10) and at Hanford, Washington. Laboratories at several universities had been for some time studying possible approaches for separating uranium isotopes (gas centrifuge, gaseous diffusion, thermal diffusion, photochemical, electromagnetic). The choice was narrowed down in late 1942 to two methods: the electromagnetic process and the gaseous diffusion process.

The first uranium isotope separation operations took place at Y-12 in fall 1943 using the electromagnetic process. The uranium fuel used in the Hiroshima bomb came from that operation. Within another year the gaseous diffusion process at K-25, a backup gamble, was proven to be a workable process and, being a continuous rather than batch operation, it was much less expensive. Y-12 was therefore, shut down in December 1946.

There was another enrichment plant that was built near K-25, the S-50 thermal diffusion plant, developed by the U.S. Navy. It operated only one year, from September 1944 until September 1945, one month after the end of World War II. These events marked the beginning of uranium enrichment.

8.1.2 Evolution of Uranium Enrichment

During World War II, the interest of the United States was in producing very highly enriched uranium (>80%) for bombs. However, in the early 1960s, the interest shifted to moderately enriched uranium (3–5%) as fuel for plants generating electricity. Reactor developers had found that when lower level-enriched uranium was used as reactor fuel, the cost of the electricity produced could be cheaper. The demand for more enrichment capacity in the 1950s and the successful operation of the gaseous diffusion plant in Oak Ridge, Tennessee, led to the construction and operation of two additional plants (Paducah, Kentucky, and Portsmouth, Ohio).

There also have been gaseous diffusion plants built in other countries, some still in operation, but the gaseous diffusion process is gradually being replaced by the gas centrifuge process. Another method of enrichment, laser isotopic separation, has generated interest in recent years.

8.2 What is Uranium Enrichment?

Enriched uranium is a critical component in civilian nuclear power generation, naval power generation and military nuclear weapons. One of the forms in which uranium exists in nature—the U-235 isotope—is fissionable, i.e., can be caused to split and release tremendous amounts of energy. To build a weapon or make it usable as reactor fuel, the desirable

U-235 isotope must be enriched from the very low concentrate (0.7%) found in nature where the balance (99.3%) is U-238. Enrichment is therefore the term used to describe processes by which the U-235 concentration is increased above its naturally occurring level.

8.2.1 Grades of Enrichment

Slightly enriched uranium (SEU) has a U-235 concentration of 0.9–2.0%, and is being used in some heavy water reactors. Low enriched uranium (LEU) has a U-235 concentration of <20%. The biggest use of LEU is in power-generating reactors at enrichment between 3% and 5%. HEU has a U-235 concentration >20%. Uranium enriched to weapon-grade and fuel for naval fleet weapons has U-235 concentrations of $\geq 85\%$.

8.2.2 Separative Work Unit (SWU)

The term SWU is used to quantify the output of the enriching plants, and to describe the supply and demand for enriching service. It is not a quantity of material. It is the measure of the effort spent to separate a given quantity into two streams, one having a higher concentration of U-235, the other lower.

8.3 Methods of Uranium Enrichment

8.3.1 Thermal Diffusion

The thermal diffusion enrichment process was developed by Dr. Philip H. Abelson for naval applications. He was asked to oversee the engineering and operations of a thermal diffusion plant, S-50, at K-25 in Oak Ridge, Tennessee, during World War II as a back-up to the other enrichment processes, which were experiencing problems.

Thermal diffusion utilizes the transfer of heat across a thin liquid layer to accomplish isotope separation. The process is based upon the fact that lighter molecules diffuse toward a hot surface, and heavier molecules diffuse toward a cold surface.

The S-50 plant built contained 2142 diffusion columns that were 48-feet high. Each column consisted of a 1 1/4" nickel pipe in the center to contain superheated steam and a slightly larger copper pipe with a precisely fixed 0.01" annular spacing for the liquid UF₆. Both pipes were surrounded by a 4"-diameter galvanized pipe for the cooling water.

The plant operated for one year, but was shut down and abandoned in favor of the gaseous diffusion process. Clusius and Dickel in Germany experimented with thermal diffusion in 1938 for other isotopes, and the Japanese tried to use the process for uranium enrichment without success during World War II. There is no known interest in thermal diffusion at this time.

8.3.2 Electromagnetic Isotope Separation

Calutrons are electromagnetic isotope separators that operate like analytical mass spectrometers. The term "calutron" is a tribute to the University of California work of E. O. Lawrence and his team of scientists who developed the process at their cyclotron laboratory and assisted in its transformation to a production-scale process at the electromagnetic plant located at the Y-12 site in Oak Ridge, Tennessee. The Y-12 calutron process was

replaced shortly after the end of World War II by the gaseous diffusion process located at the K-25 plant (also in Oak Ridge). The gaseous diffusion operation had much larger production capabilities and was far less labor intensive.

A calutron is a mass spectrometer with much higher material throughput than a typical mass spectrometer used for analytical purposes. Because of this high throughput, it is very useful for producing milligram to multi-kilogram quantities of enriched isotopes for a wide variety of applications, ranging from nuclear weapons to nuclear medicine, and for research to industrial-scale quantities.

In a calutron, the feed material, composed of an element with multiple isotopes, is vaporized by heating in a vacuum. It must be in a chemical form (elemental or compound) that has sufficient vapor pressure between room temperature and approximately 1000°C to form adequate amounts of vapor for the process. This vapor passes into an electron plasma ionization chamber which ionizes the atom, ideally, to a +1 charge. The ions are then extracted by high voltage to form an ion beam. The entire process takes place within an intense magnetic field which bends the ion beam in a semi-circular path. The light ions are bent by the magnetic field into a tighter radius than the heavier ions.

With the proper combination of accelerating voltage and magnetic field suited to the range of masses being separated, discrete ion beams of each isotope in the feed material can be formed and spatially separated sufficiently to be physically collected.

Although the enrichment of uranium by calutrons was discontinued in 1946, 72 of the 1152 calutrons remained in operation for the separation of isotopes for research in medicine, agriculture, industry, and biology. Eight calutrons were still in operation in 1997.

Because of its use in the Manhattan Project, the details of the electromagnetic isotope enrichment process were highly classified. After the discontinuation of its use for enrichment of uranium, much of the related technology was declassified and made available to the rest of the world through conferences and technical publications. Many countries developed their own electromagnetic isotope enrichment capability, but much smaller in scale. While the individual separators were similar in size and design, the number of separators, and thus the total production capability, was much smaller. Russia pursued a course similar to the United States in their atomic weapons development program, and after developing improved techniques, converted the facility to stable isotope enrichment. During the first Gulf War in the early 1990s, it was discovered that Iraq had attempted to use this method as a part of its atomic weapons development program. The end of the war put an end to those efforts. From that lesson the process remains a nuclear proliferation concern.

8.3.3 Gaseous Diffusion

8.3.3.1 Background of Gaseous Diffusion

After the discovery by Otto Hahn and Fritz Strassman that uranium atoms could be split when bombarded with neutrons, physicists all over the world rushed to their laboratories to confirm this finding. One was a laboratory at Columbia University. John Dunning, an experimental physicist, joined in early theoretical discussions with Enrico Fermi, Leo Szilard, Edward Teller and occasionally Eugene Wigner. Dunning later worked with Eugene T. Booth in studying methods of diffusion. They settled on gaseous diffusion as being the best bet. British physicists came to the same conclusion at about the same time.

Dunning and Booth then began to develop the idea of gaseous diffusion. In January 1941, they could demonstrate a very-small-scale enrichment of U-235. The demonstration brought in support for further work on gaseous diffusion and, over the next three

years, their program grew and expanded to the development of the process used for the K-25 plant in Oak Ridge. In December 1942, the decision was made by the management of the Manhattan District to use the electromagnetic process and have gaseous diffusion as a backup. Construction was then started on facilities for both processes in Oak Ridge, Tennessee. The electromagnetic plant was operated until 1946 because gaseous diffusion proved to be a more efficient method. The unit cost of enrichment by gaseous diffusion was less than 10% the cost of electromagnetic enrichment. Thus, gaseous diffusion became the sole process for the enrichment of uranium in the United States.

In 1945, enrichment capacity was increased by the addition of a second building in Oak Ridge, and in the early 1950s three more buildings were added to the same site. In 1952, a plant was built in Paducah, Kentucky. In 1956, yet another plant near Portsmouth, Ohio, went into production.

The end of operating the complex at full capacity to produce highly enriched uranium for the U.S. nuclear weapons stockpile was reached in 1964. The original plant at Oak Ridge (commonly referred to as the "U" because the mile-long building was folded into the shape of a giant letter "U") was shut down. The Portsmouth Plant continued to produce highly enriched uranium, up to 97 weight percent for the nuclear fleet reactor fuel.

The advent of commercial nuclear power reactors spawned a new mission from 1965 to 1985 for the diffusion plants—production of enrichment between 3% and 5% for domestic and foreign reactors. The productive capacity of the Oak Ridge, Paducah and Portsmouth complex in the 1960s was 10 million kilogram SWUs per year. By 1971, the capacity had been increased to 17.2 million SWU per year.

A major program was started in early 1972 to increase the productive capacity of the diffusion complex through efficiency improvements and equipment uprating. At the completion of the program in 1981, the capacity of the complex when at full power was 27.3 million SWUs per year. In 1974, plans were started for additional diffusion production capacity by adding a new building at Portsmouth. The diffusion equipment was to be larger than that in operation at that time. However, in 1977 this program was cancelled in favor of a Gas Centrifuge Enrichment Plant to be built at the Portsmouth site.

In 1985, after eight years of design and construction and billions of dollars spent, the Centrifuge Plant and all R&D was stopped by Washington in favor of the development of a process using lasers (Atomic Vapor Laser Isotopic (AVLIS) process) that the Lawrence Livermore National Laboratory (LLNL) argued would be cheaper than any centrifuge present or future. At the same time, 5 June 1985, Washington, faced with a falling share of the market and increasing power costs, decided to operate only the Portsmouth and Paducah plants, and shut down all Oak Ridge diffusion operations.

In 1992, a government-owned corporation, United States Enrichment Corporation (USEC) was formed and given the responsibility for the U.S. enrichment programs, including operation of the Paducah and Portsmouth plants. In 1998, USEC was privatized. In 2002, the highly enriched operations at Portsmouth were discontinued, and in 2004 all diffusion enrichment at Portsmouth was shut down. This left Paducah currently as the only enrichment facility in the United States.

France and China are the only other countries operating gaseous diffusion enrichment plants. The British and Russians previously operated gaseous diffusion plants. The British plant was shut down several years ago and the Russian plant was converted to a centrifuge plant. The French are underway with plans for a centrifuge plant. When USEC and the French have centrifuges operating, we will see the last of gaseous diffusion, largely because the centrifuge process requires so much less (<5%) electrical power than does diffusion.

8.3.3.2 Gaseous Diffusion Process

The fundamental principle on which the gaseous diffusion process is based was discovered by a Scotsman, Graham, in 1829. Graham showed that the average velocities of gas molecules at a given temperature depended upon their masses. Therefore, in a gas made-up of molecules containing different isotopes, molecules containing the lighter isotope will, on average, have velocities a little faster than those containing the heavier isotope. It is this small but useful velocity difference which the gaseous diffusion process utilizes.

If the gaseous mixture is forced under pressure against a suitable porous membrane or "barrier," more of the lighter molecules will flow through the pores due to their higher velocity. To maximize the amount of separation achieved, the barrier material must meet exacting standards so that "diffusive" flow occurs, i.e., pore sizes must be such that individual molecules collide only with the pore walls rather than with each other. Diffusive flow requires not only small barrier pores (less than two-millionths of an inch in diameter), but also uniformity of pore size.

Because the amount of separation that can be realized by one pass through barrier material is dependent on the difference in mass of the molecules, very small gaseous mixtures of U-235 and U-238 must undergo this diffusion process many times for meaningful separation. It is the achievement of the gaseous diffusion industry that this delicate and demanding physical process was harnessed on a huge production scale to enrich uranium in a reliable manner.

The gaseous compound used to carry out the diffusion is uranium hexafluoride (UF₆). Various physical and chemical properties of UF₆ make it the only known suitable compound. It is a solid at room temperature; consequently, the diffusion plant had to operate at temperatures and pressures to maintain UF₆ in gaseous form. Although it is a stable compound, UF₆ is extremely reactive with water, very corrosive to most common metals, and incompatible with organic materials (e.g., lubricating oils). This chemical activity dictates the use of metals such as nickel and aluminum, and means that the entire process flow system must be leak-tight and clean. The corrosiveness of the process gas also makes barrier production more difficult because the barrier quality must be maintained over many years of operation.

The basic concept of gaseous diffusion is illustrated in Figure 8.1. It shows what takes place in any single stage in the process system. Gaseous UF₆ is introduced into the "diffuser" or "converter" under pressure and made to flow along the inside of barrier tubes. About one-half of the gas diffuses through the barrier and is fed to the next higher stage; the remaining undiffused portion is recycled to the next lower stage. The diffused stream

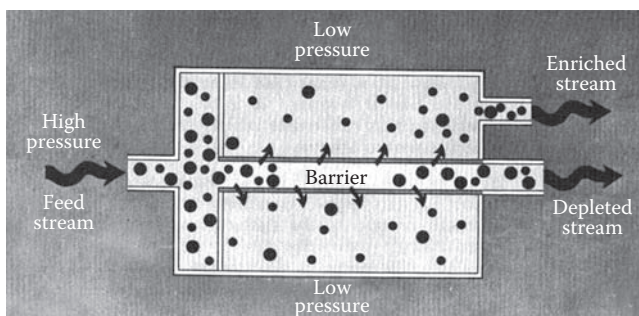


FIGURE 8.1
Gaseous diffusion stage.

is slightly enriched with respect to U-235, and the undiffused stream is depleted of U-235 to the same degree (Figure 8.2).

Single stages are connected together (Figure 8.3) so as to accomplish significant enrichment. Figure 8.3 also indicates the basic equipment components vital to the process. Axial flow compressors are used in the larger stages to compress the gas to maintain the inter-stage flow. The compressors are electrically driven. A gas cooler is incorporated in each converter to remove the heat of gas compression. Groups of stages are coupled in this way to make-up operating units, which in turn make up the entire "cascade."

Viewed as a whole, UF₆ "feed" with a U-235 assay of 0.71% is introduced into the middle of the cascade. From there, U-235 selectively moves toward the top of the cascade and is withdrawn as "product" at various points depending upon the desired enriched level.

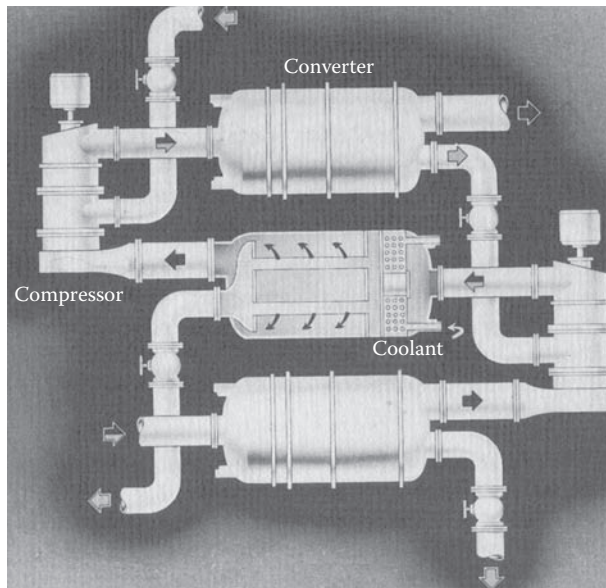


FIGURE 8.2
Gaseous diffusion stage arrangement.

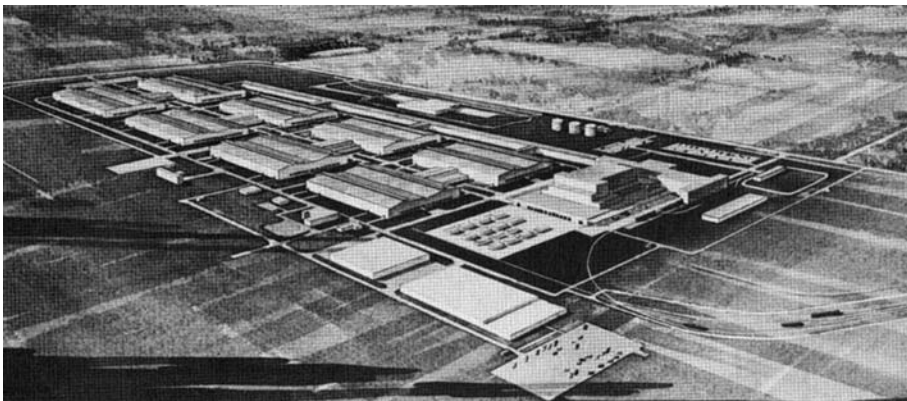


FIGURE 8.3
Conceptual drawing of the DOE-planned Portsmouth centrifuge plant (1980).

Similarly, the U-238 selectively moves toward the bottom of the cascade and is withdrawn and deleted or “tails” material. This depleted material contains about 0.2% U-235 and has been stored at all three plants since operations began for possible future use.

8.3.4 Gas Centrifuge

8.3.4.1 Background of Gas Centrifuge Enrichment

The idea of using centrifugal or gravitational forces to separate a mixture of gases of different molecular weights is very old. Experiments to this end were conducted in Germany as early as 1895. The extension of the method to separate isotopes had been suggested soon after researchers had discovered their existence. In 1919, the physicists Lindemann and Aston suggested that centrifuges might be used to separate isotopes, but it was not successfully accomplished until 1935 by Jesse Beams at the University of Virginia. He succeeded in separating the isotopes of chlorine and, with the 1939 German discovery of nuclear fission, went to work quickly on uranium. By 1941, he had enriched gram amounts of uranium to 5% U-235.

In mid-1942, the National Academy of Sciences, being asked for their assessment of what processes should be used in the Manhattan Project, recommended gas centrifuge and gaseous diffusion. Beams had more advanced hardware and experimental data than the Columbia Diffusion Team or the California Electromagnetic Team. A pilot plant was designed, constructed and operated by industrial teams at the Baytown, New Jersey refinery of Standard Oil. There were 24 commercial centrifuges of diameter 7.2 inch, 42-inch long rotors, with an overall height four times that long because of the complex bearing and gas systems. Some ran successfully, some failed. The Manhattan experts toured the facility and talked to the engineers, but decided the mechanical complexities of the many thousands of machines needed were too great. So the centrifuge program was stopped.

In 1958, there was a revival of the gas centrifuge brought about by the work of the Austrian Gernot Zippe. He had been working in the USSR on a R&D effort on gas centrifuge and had come-up with a revolutionary mechanical design. Beams heard of this, and talked Zippe into coming to the United States in 1958 to work with him.

In 1960, under an AEC contract, research and development of the centrifuge began at the K-25 site in Oak Ridge by a team of engineers from Union Carbide (operating contractor to AEC), University of Virginia, and a little later Garrett AI Research of Torrance, California. Over the next two decades, significant advances led to much longer, faster and more efficient machines, and to a full-scale demonstration that was convincing enough for President Carter to announce in his energy message in April 1977 that the next U.S. uranium endeavor would be a gas centrifuge plant instead of an “add-on” gaseous diffusion facility as originally planned. It was later determined that the centrifuge plant would be built at Portsmouth, Ohio, adjacent to the gaseous diffusion plant (Figure 8.3).

Development work continued to further increase the output and reduce the cost of the machines while construction of the plant proceeded. However, in June 1985, the Department of Energy (DOE) made the decision (after an expenditure of nearly \$3 billion) to shut down the centrifuge plant and concentrate on the development of the AVLIS process for uranium enrichment at LLNL.

The Energy Act of 1992 established a government corporation, USEC, for the enrichment operations that had been under the DOE. In 1998, USEC became completely private. USEC took over the continuing development of AVLIS. In 1999, USEC discontinued all work on AVLIS and began an investigation of alternative methods of enrichment. In 2002,

the decision was to reactivate the centrifuge program. A research and development program was initiated to improve upon the machine using latest materials and technologies. The centrifuge plant will be located at the site of the past Portsmouth, Ohio, diffusion plant and will use very large buildings that were put up for the DOE centrifuge program in the 1980s. A Lead Cascade Test Program began at the site in August 2007. The purpose of the Lead Cascade is to validate the feasibility of closed-loop cascade operations and demonstrate the capability of the technology to produce low enriched uranium at commercial product assay levels.

USEC has released the information that its centrifuge rotor will be 40-feet high, about 2 feet in diameter, and made of tightly woven carbon fibers. The rotational speed remains a secret. The machine capacity will be 350 SWUs per year. The announced total centrifuge plant output will be 3.8 million SWUs per year. Complete plant operation is scheduled to be achieved in 2012.

There will be two other enrichment plants in the United States. One is under construction in Eunice, New Mexico, by Louisiana Energy Services (a U.S. company formed by Urenco Enrichment Company). The announced capacity of this plant is 3 million SWUs per year starting in 2010. Urenco is a European private sector consortium with plants in Germany, the United Kingdom, and the Netherlands. Urenco was the first commercial entity to enrich uranium on a production scale (centrifuges started in 1977) and is currently the world's largest single provider of centrifuge-enriched uranium. The other centrifuge plant is being planned by Enrichment Technology Company, a U.S. division of Areva, a French company. The announced planned capacity of this plant is 3 million SWUs per year starting in 2013. The location site has not been determined.

Other countries using (or planning to use) centrifuge technology are Russia, Japan, China, North Korea and Brazil. The first centrifuge plant in France is under construction with full operation scheduled for 2009. Iran has had a gas centrifuge plant under construction for several years. The existence of the site became publicly known in August 2002. According to the International Atomic Energy Agency (IAEA) the Iranian centrifuges are based upon first-generation Urenco designs.

8.3.4.2 Gas Centrifuge Process

A gas centrifuge comprises an evacuated casing containing a cylindrical rotor which rotates at high speed in an almost friction-free environment and into which gaseous UF₆ is fed. It works with the small difference in molecular weight between UF₆ molecules containing the U-235 atom and those containing the U-238 atoms. The difference is exploited by imposing an artificial gravitational field on the gaseous mixture of the two isotopes, creating a radial concentration gradient which then becomes an axial gradient with countercurrent flow on the inner part in one direction and along the wall in the opposite direction. The degree of enrichment in a single centrifuge machine is dependent upon the mass difference of the isotopes being separated, the length of the rotator, and the speed of rotation. The principle of a gas centrifuge is illustrated in Figure 8.4.

The UF₆ introduced near the center of the rotor accelerates to approximately the speed of the rotor. Centrifugal force causes the heavier U-238 molecules to move closer to the wall of the rotor, producing partial separation of the U-235 and U-238 isotopes. This separative effect is increased by an axial countercurrent flow of gas within the rotor. The enriched UF₆ is removed through a scoop at the top, and the depleted through a scoop at the bottom.

Because the desired enrichment is not obtained in a single centrifuge, several machines must be connected in a series, known as a "cascade" (Figure 8.5).

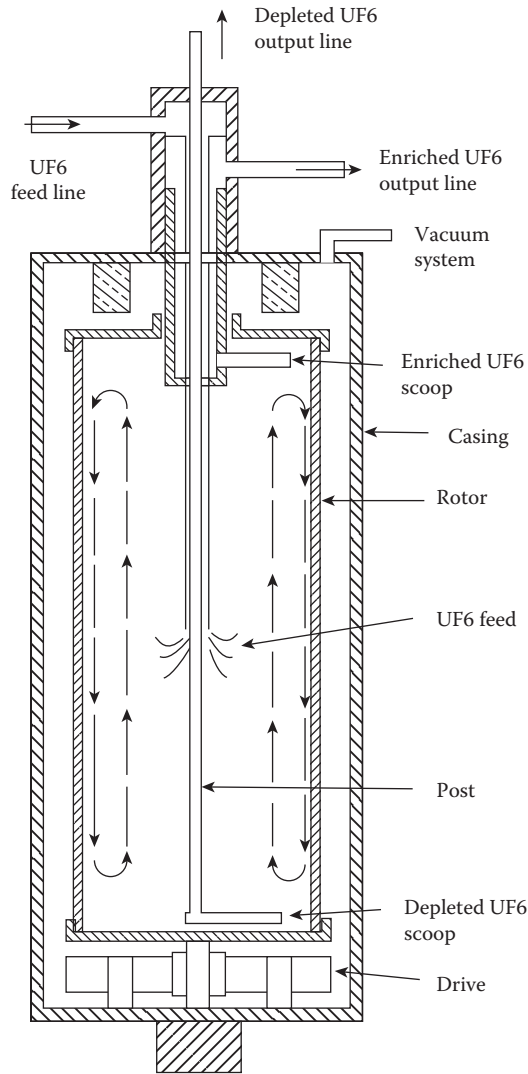


FIGURE 8.4
Cutaway drawing of a gas centrifuge.

Only a small amount of gas will flow through a single centrifuge. Therefore, many machines must be connected in parallel to achieve the total flow necessary for a large capacity plant.

Even though the separation achieved per machine is much greater than in a diffusion stage, it is much smaller than needed for most applications. Many machines must therefore also be connected in series to achieve the total enrichment required. In a centrifuge cascade, the largest number in parallel will be at the feed point with decreasing numbers as the enrichment levels increase toward the desired product enrichment.

The separation factor for a centrifuge varies with the fourth power of the speed, thus the desire to operate at the highest speed possible. This in turn means that the rotor must be made of a material that has the highest strength-to-density ratio possible. USEC has

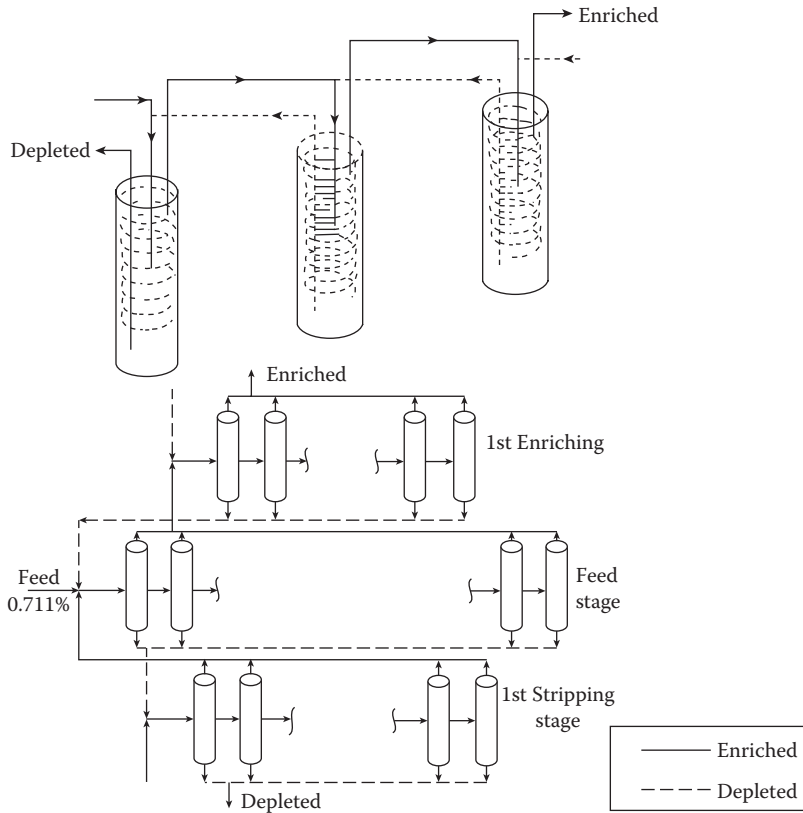


FIGURE 8.5
Configuration of gas centrifuges.

released the information that the rotor in the “American Centrifuge” is made of tightly woven carbon fiber.

8.3.5 Laser Isotope Separation

8.3.5.1 Laser Isotope Background

The invention of lasers in the early 1960s made possible the laser isotope separation (LIS) approach. The first U.S. research began in the 1960s at the Los Alamos National Laboratory (LANL); lasers were used to excite the U235 F6 molecules in a UF6 stream, a process they called “Molecular Laser Isotope Separation” (MLIS). Their work continued for a decade or more, showed promise, but was phased-out during the late 1970s. Not long after the MLIS work was underway, the LLNL started research on a complementary approach using lasers to excite U235 atoms in a stream of uranium metal vapor (AVLIS). Their work progressed over the next 30 years, being finally phased-out in 1999. There was one private venture by Exxon Nuclear Company. They worked on laser enrichment technology for approximately 7 years before phasing out.

In France, research started soon after on a program (SILVA). It was reported in 1975 that enriched uranium had been produced in small quantities. In Germany, a small-scale

research program was started in 1971. Israel was doing research on laser separation in 1973, but kept it under wraps. However, convincing reports were that Israel had a cheap but sophisticated laser process, and later received a German patent. Japan initiated its research program in 1975 and reported in 1977 that they had collected a microgram of uranium at a concentration of 35% U-235 in a successful experiment. Italy stated research work in 1977. The Soviet Union was known to be working on laser isotope separation and in 1979 published articles on uranium including LIS. However, the most active programs were in the United States.

In 1978, the U.S. Congress clamped a secrecy label on laser separation of uranium retroactive to 1976 due to concerns that, because of costs of construction and operations being much lower for a laser separation plant than for diffusion and centrifuge plants, enrichment plants could be available to small nations and lead to proliferation. Funds were cut from the Federal energy budget for laser enrichment.

The Energy Research and Development Agency (ERDA), the forerunner to the DOE, through the late 1970s to 1981 supported the study of three new experimental processes for uranium enrichment. Two were based upon laser separation, and one on plasma separation. Jersey Nuclear-Avco Isotopes Incorporated (subsidiary of Exxon) and the LLNL worked on atomic uranium vapor. LLNL referred to it as AVLIS. The LANL and a group at Exxon Research Laboratories (not connected with Jersey-Avco) worked on molecular UF₆. TRW Incorporated pursued research work on a plasma separation process. Union Carbide Nuclear Division (UCC-ND) supported each in their efforts. In 1981, the AVLIS process at LLNL was selected as the process to be developed further and the other processes were subsequently phased out.

Throughout the first half of the 1980s, there was a continued erosion of the U.S. share of the enriched uranium market as a result of stiff competition from French Eurodif and Urenco. The U.S. monopoly in the early 1970s dropped to 47% in the next decade. At prodding from Congress, the DOE began to address the issue of how to best provide technology for future competition. In mid-1984, the process was begun with the appointment of a process evaluation panel which was given the task of recommending to the Secretary of Energy which of the two advanced technologies (advanced centrifuges or AVLIS) was to be the replacement for the diffusion operations. There followed a string of debates between teams from each side before the panel, which culminated in the selection of AVLIS as the favored program for the future. The announcement by the Secretary of Energy was that concentration thereafter was to be on the development of AVLIS as the sole advanced enrichment technology and included shutting down as soon as possible the gaseous diffusion plant at Oak Ridge, Tennessee, and the immediate discontinuation of the gas centrifuge plant program at Portsmouth, Ohio, and development work on centrifuge processes.

The advantages of AVLIS over gaseous diffusion and gas centrifuge were seen as:

- Requirement of only a single step to enrich uranium compared with the sequential steps required in gaseous diffusion and gas centrifuge
- Ability to extract nearly all of the U-235 from the feedstock
- Ability to reprocess the depleted UF₆ resulting from the diffusion operations
- Lower cost plant to construct and operate

DOE supported the development work of AVLIS at LLNL until 1994 when the USEC became an entirely private company. At that time, DOE turned the program over to USEC

for continuation. In the first-half of 1999, USEC gave-up on AVLIS and started to search for a replacement.

Upon the closure of AVLIS, the only remaining laser process on the world stage was (Separation of Isotopes by Laser Excitation (SILEX), a molecular separation process developed by the Australian company Silex Systems Limited. The French had ceased work on their laser program, SILVA, in 2003.

In 1996, USEC secured the rights to evaluate and develop SILEX, but relinquished those rights in 2003, having earlier decided to reopen the advanced centrifuge program.

In early 2006, General Electric announced the signing of an exclusive agreement with Silex Systems Limited to license the technology and develop the next generation low-enriched uranium manufacturing process in the United States. The transaction will require regulatory controls and government approvals. GE has had meetings with the U.S. Nuclear Regulatory Control (NRC) and plans to submit a license application in December 2007 and receive approval in 2009. The first phase would be a test loop in GE's existing fuel manufacturing facility in Wilmington, NC.

8.3.5.2 Laser Separation Processes

The gaseous diffusion and gas centrifuge techniques exploit the small mass differences between U-235 and U-238 in the gaseous form of UF₆. AVLIS is based on an entirely different concept. U-238 and U-235 isotopes have different electron energies, so that they absorb different colors of light. Lasers are tuned to emit a carefully chosen combination of colors that will be absorbed by only U-235. The laser-excited U-235 atom emits an electron and becomes a positively charged ion. The U-235 ions are then separated from neutral U-238 using electromagnetic fields.

The AVLIS process consists of a laser system and a separator system. The latter contains a vaporizer and a collector. The working medium is metallic uranium that is melted and vaporized to form an atomic vapor stream. The vapor stream flows through the collector where it is illuminated by precisely tuned laser light. The selected atoms become charged by photoionization and are removed from the vapor stream by an electronic field.

The laser system is a laser-pumped laser, i.e., one laser system is used to energize a second, which finally produces the light used in the separation process. This allows the separation of the requirements for efficiency and color precision. The large pump lasers are reasonably efficient, whereas the dye lasers (which convert the pump laser light to process light) are tunable, reliable and commercially available.

When the laser light illuminates a stream of uranium vapor, the U-235 vapor absorbs the light, but the U-238 does not. The now excited U-235 ejects an electron, thus becoming a positively charged atom or ion which is deflected by an electromagnetic field to the product collector. The U-238 remains uncharged and passes through the collector section to the tails collector.

The vaporization of the uranium is accomplished by means of an electron beam that creates an atomic U-235/U-238 vapor stream.

MLIS uses UF₆ as its feedstock, thereby fitting more readily into the conventional fuel cycle than AVLIS. There are two steps involved in the MLIS process: excitation with infrared lasers and then dissociation with an ultraviolet laser. Gaseous UF₆ mixed with a carrier gas (argon) is expanded through a nozzle that cools the gas to low temperatures. The UF₆ is irradiated by infrared lasers, which selectively excite the U-235F₆, leaving the U-238F₆ unexcited. Photons from an ultraviolet laser then preferentially disassociate the excited

U-235F₆ to form U-235F₅ and free fluorine atoms. The U-235F₅ formed in this manner precipitates from the gas as a solid powder which can be filtered from the gas stream.

8.3.6 Plasma Separation

The plasma (fluid or vapor composed of charged particles) method of separation is based upon the fact that the cyclotron frequency of an ion in a magnetic field is a function only of the ion mass and the magnetic field strength. Accordingly, by exciting a plasma comprising uranium ions and electrons at the cyclotron frequency of the U-235 ions, it is possible to "pump energy" into the U-235 selectively and thereby increase the orbit diameter of the U-235 ion relative to that of the U-238 ion. Collection schemes are based on the difference in orbit diameter between the U-235 and U-238 ions as they traverse the length of the plasma orbiting around the field lines of a high-strength solenoidal magnet. The excitation of the U-235 is accomplished by placing in this plasma a radiofrequency antenna tuned to the U-235 cyclotron frequency. The separation performance of a single separator is adequate enough to cover the isotopic gradient of interest so that staging will not be required.

8.3.7 Aerodynamic Processes

There have been two aerodynamic separation methods developed and tested. One, in Germany, is the separation nozzle, referred to as the "Becker jet nozzle." The other is the vortex tube separation technique developed in South Africa. In both processes, the separation results mainly from centrifugation induced in a gas stream deflected by a duly shaped stationary wall. UF₆ is used in both cases. Enhancement of centrifugation is achieved by dilution of the UF₆ with a light gas (hydrogen or helium). Addition of the light gas in molar excess is to increase the UF₆ flow velocity attainable at a given pressure ratio. Negative features are high energy requirements and removal of waste heat problems. Neither method has been in use for some time.

8.3.8 Chemical Exchange

The French did investigative work on chemical exchange in the last-half of the 1970s, but found the separation effect for uranium to be too small for practical application. There is no current use of this method for uranium.