Isotope Separation, with a Focus on Uranium Enrichment

ISIS Course

October 30, 2014

Isotope Separation

- Uranium enrichment is a form of isotope separation.
- Isotope separation is extremely hard to do, since the separation involves separating constituents of the same element, namely isotopes
- Isotopes are atoms of the same element with different atomic weights, i.e. the same number of protons but different number of neutrons
- Isotopes behave quite differently in nuclear reactions but have only slightly chemical and physical properties, rendering standard methods of purification unusable.
- Isotope separation is typically the enrichment, or increase of the fraction, of the desirable isotope

Isotope Separation Related to Nuclear Proliferation-Key Isotopes

- Deuterium (D)
- Lithium 6 (Li 6, or ^{6}Li)
- Uranium 235 (U 235, of ^{235}U)

Deuterium

- Deuterium is a stable hydrogen isotope with two neutrons and one proton
- It's natural occurrence is 0.015 percent, where the deuterium is in water form (D_20).
- After concentration, it is called heavy water and as we discussed earlier is a moderator for reactors, which mainly use natural uranium. Nuclear or reactor grade has a concentration of 99.75% deuterium.
- Deuterium is also used in thermonuclear weapons, where much of the explosive yield results from the fusion of the hydrogen isotopes deuterium and tritium.
- It is used in a long-shelf-life neutron initiator used to start the chain reaction in a fission weapon
- It is produced in a variety of ways. For example, the Girdler sulfide (GS) process is used to produce heavy water with about 15% deuterium (D), then a distillation process can concentrate the deuterium up to reactor grade, or 99.75% D. For more information on heavy water production, see http://en.wikipedia.org/wiki/Girdler_sulfide_process and http://www.fas.org/nuke/intro/nuke/heavy.htm

Iran’s Arak Heavy Water Production Plant

ISNA/PHOTO:ARASH KHAMOOSHI

Iran's Arak Heavy Water Production Plant

Pakistan's Khushab Heavy Water Production Plant in 2000

http://isis-online.org/isis-reports/detail/analysis-of-ikonos-imagery-of-the-newly-identified-heavy-water-plant-at-khu/12

The newly-identified heavy water plant at the Khushab site in Pakistan

Lithium 6 (Li 6)

- Li 6 is a stable isotope with a natural abundance of 7.56 percent.
- It is enriched typically to 40-95 percent
- Li 6 is used to produce tritium for nuclear weapons, where tritium is a hydrogen atom with three neutrons
  - Tritium is typically produced through irradiation of Li 6 in a reactor, whereby Li 6 plus a neutron yields helium 4, tritium, and energy.
- Lithium 6 is also used directly in thermonuclear weapons as a way to produce tritium during the explosion via irradiation by neutrons produced by fission and fusion.
- Almost all lithium 6 produced by the United States was enriched by the mercury-based Column Exchange process (COLEX) from 1954 to 1963. For more information on this process and US production, see https://www.osti.gov/opennet/forms.jsp?formurl=document/press/pc23.html

Uranium 235 and Uranium Enrichment

- Concentration of uranium 235 above its natural value is called uranium enrichment
- Natural uranium is composed of:
  - 0.0054% uranium 234 (92 protons, 142 neutrons)
  - 0.72% uranium 235 (92 protons, 143 neutrons)
  - 99.26% uranium 238 (92 protons, 146 neutrons)
- Uranium is enriched to 3-5 percent uranium 235 for use in fuel for nuclear reactors.
- It is typically enriched to 90 percent uranium 235 for use in nuclear weapons.

Uranium Critical Mass

- Critical mass is the smallest amount of enriched uranium that can maintain a chain reaction
- For enriched uranium, the critical mass depends on the fraction of uranium 235
- The values in the next slide assume enriched uranium is in a spherical shape and in metal form, and surrounded by a good neutron reflector, such as beryllium. The neutron reflector serves to reflect the neutrons back into the metal sphere of enriched uranium.

Percentage of Uranium 235	Critical Mass (kilograms)
100	15
90	18
75	25
50	50
20	250
10	1250
5	Not possible to achieve a bare sphere critical mass

Bare Sphere Critical Mass (source DOE)

Note: The critical mass increases rapidly as the percentage of uranium 235 decreases.

Uranium Enrichment Processes

- Many methods have been developed to increase the fraction of uranium 235.
- Some were unwieldy, inefficient, expensive but developed out of necessity:
  - The Electromagnetic Isotope Separation (EMIS) method was used in the Manhattan Project in World War II and the 1990s Iraqi nuclear weapons effort. The Iraqi project was incomplete in January 1991 when the project stopped due to the war. The EMIS project in the Manhattan Project produced the HEU used in the Hiroshima bomb. No other enrichment method was ready to make HEU by August 1945.

EMIS Separator

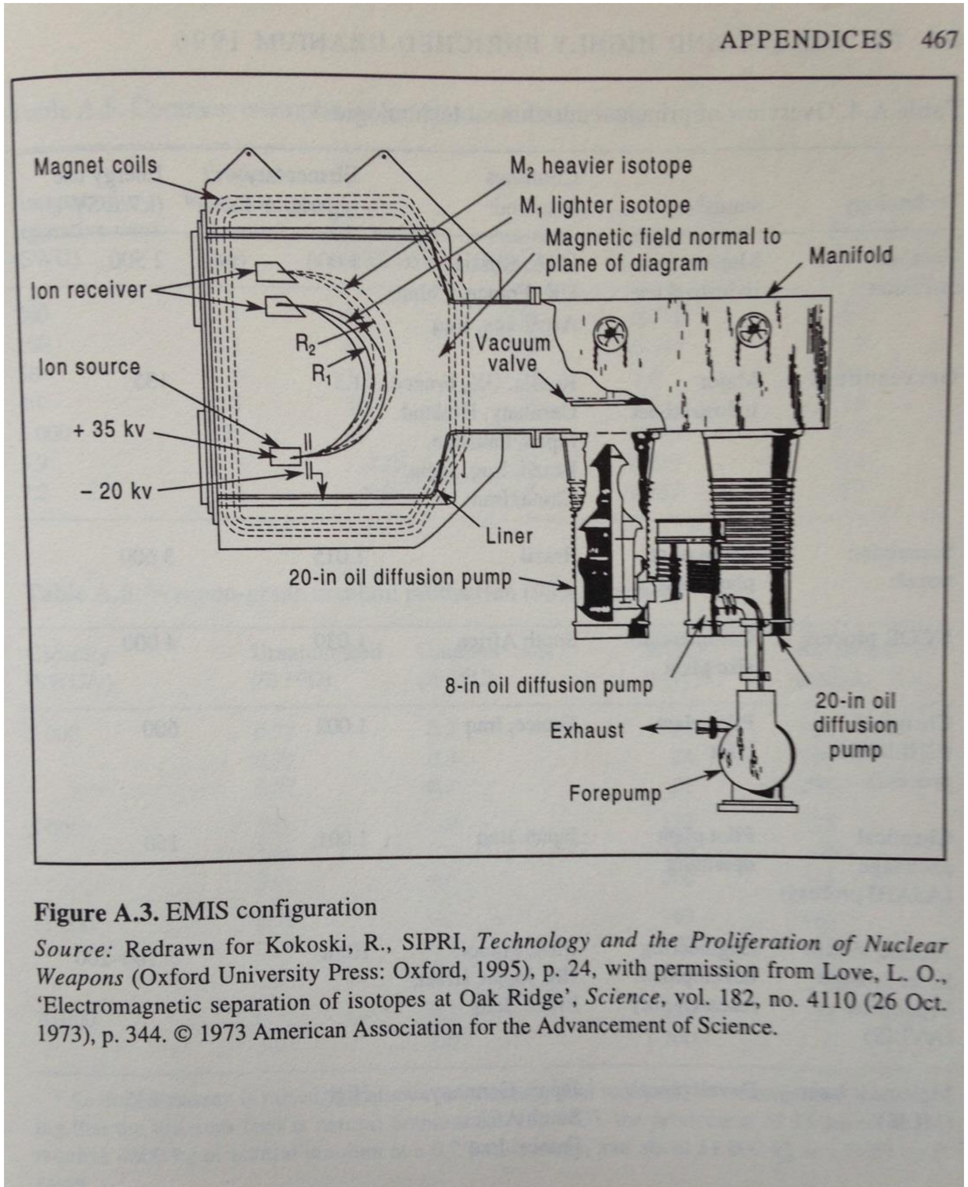

APPENDICES 467

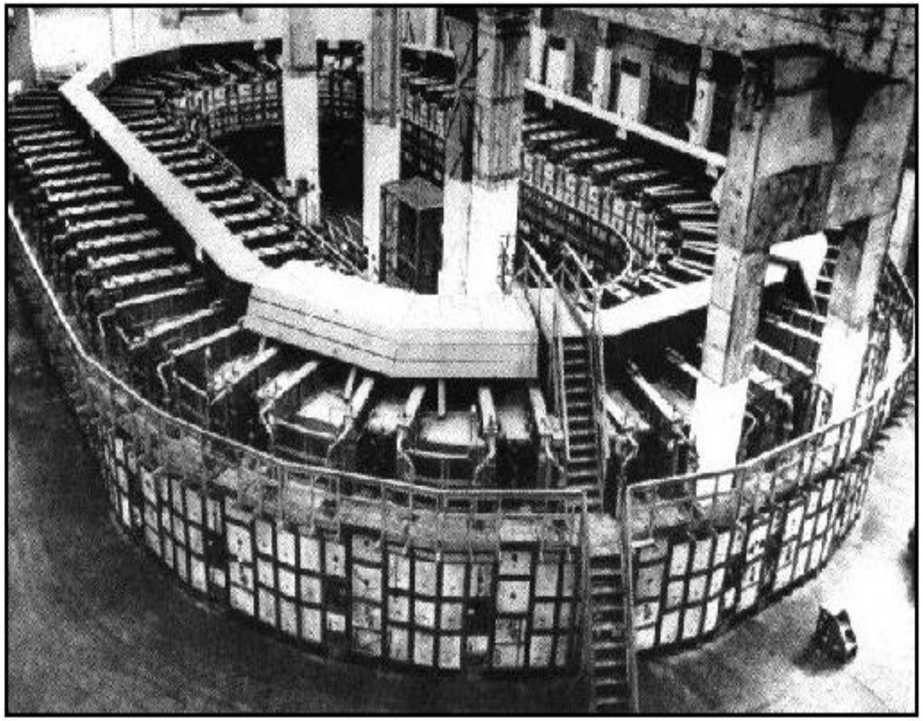
Figure A.3. EMIS configuration

Source: Redrawn for Kokoski, R., SIPRI, *Technology and the Proliferation of Nuclear Weapons* (Oxford University Press: Oxford, 1995), p. 24, with permission from Love, L. O., 'Electromagnetic separation of isotopes at Oak Ridge', *Science*, vol. 182, no. 4110 (26 Oct. 1973), p. 344. © 1973 American Association for the Advancement of Science.

Iraqi EMIS pole piece, part of magnet of alpha separator, seized in desert in 1991
https://newsline.llnl.gov/_rev02/articles/2009/mar/03.13.09-dreicer.php

First Stage EMIS Separators at Oak Ridge, TN in the Manhattan Project

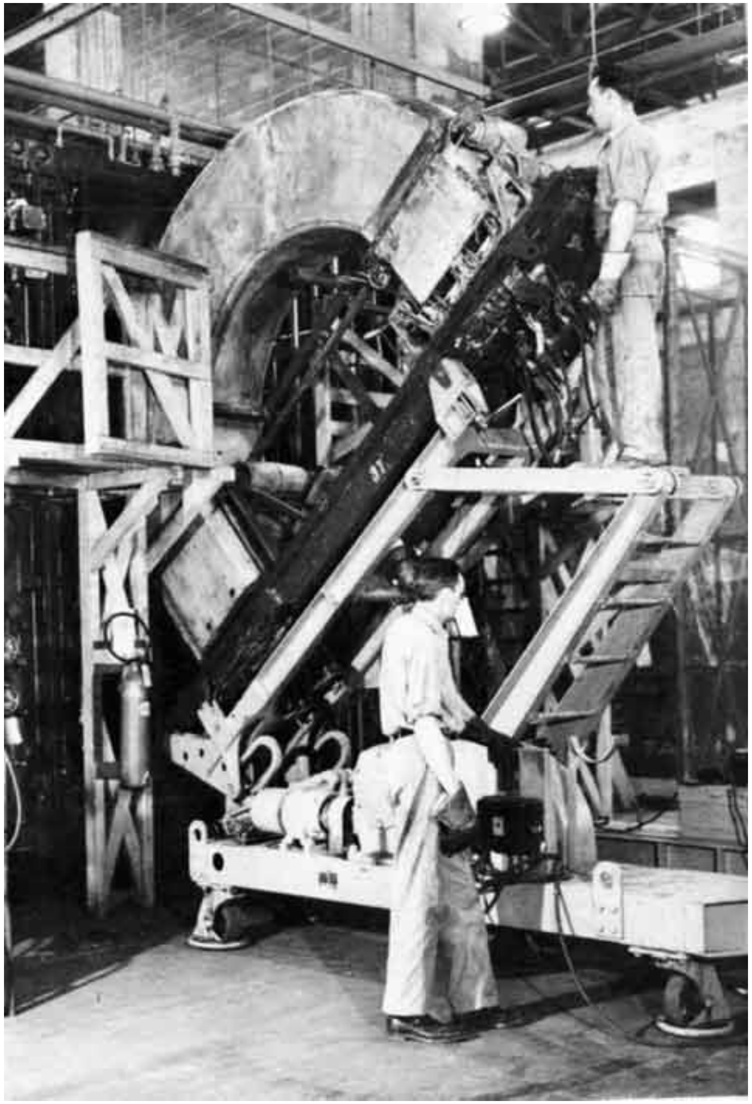
- Alpha, or first stage, separators organized into a production unit, called a “racetrack” of 96 separators, of “calutrons”
- The second stage involved smaller separators called beta separators
- The two stages working sequentially enriched uranium from natural to 75-90 percent enriched uranium, where the alpha separator enriched up to 10-12 percent, and the beta separator the rest of the way.
- The project at its peak employed 24,000 people and involved five alpha track buildings. four beta separator buildings, and many buildings involved in uranium conversion and uranium recovery
- In terms of technical difficulty, the WWII EMIS project is said to compare to the placement of a permanent mission on Mars in a period of 4-5 years.

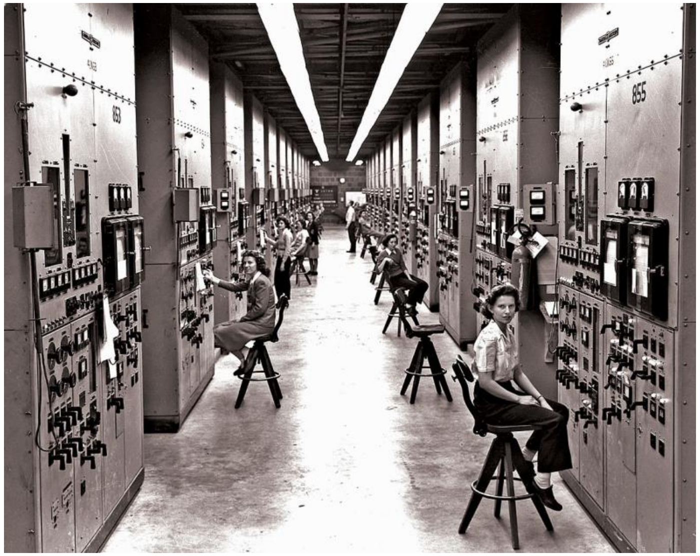


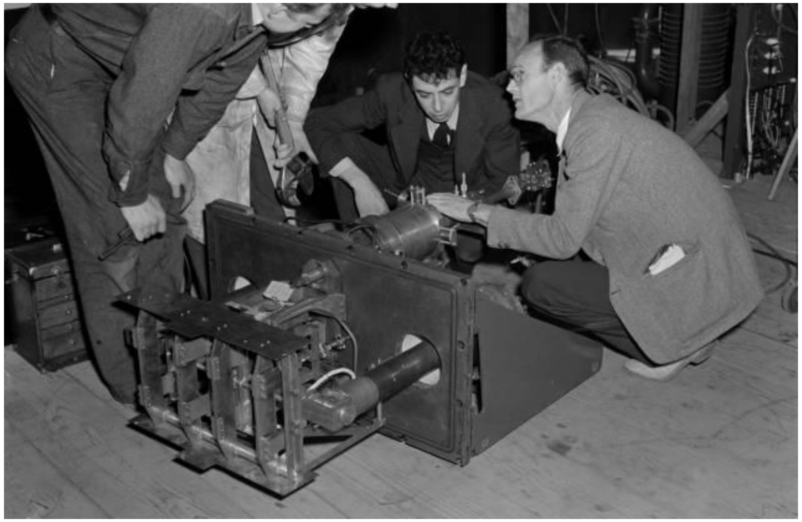
Y-12 alpha 1 racetrack - Courtesy of the Department of Energy

Calutron Facility at Oak Ridge, TB

http://en.wikipedia.org/wiki/Calutron





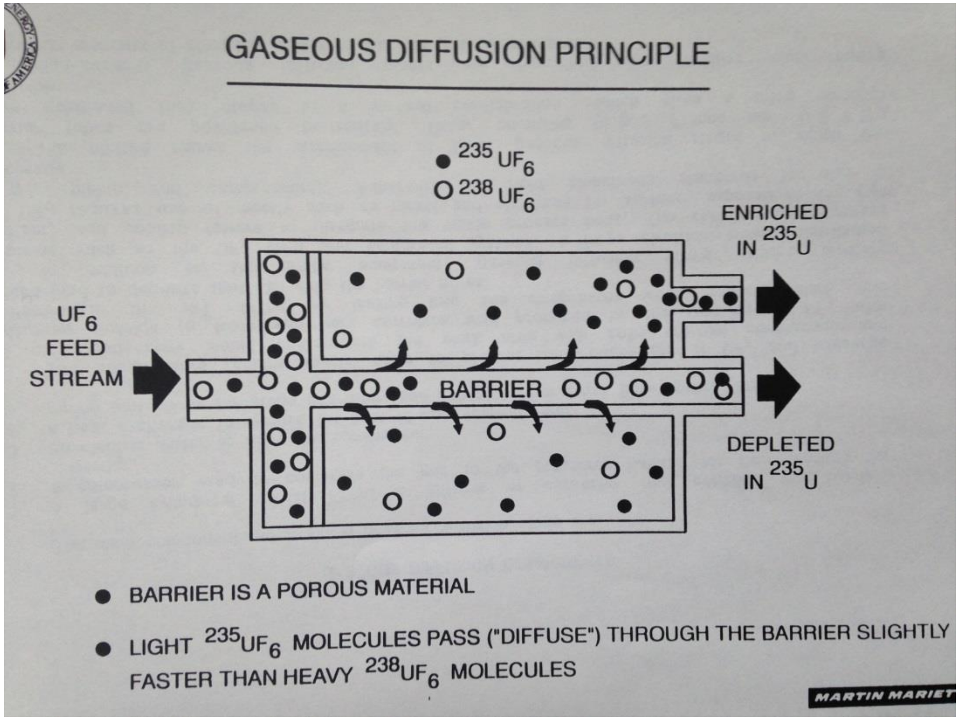


Aerodynamic Uranium Enrichment Process

- Another unwieldy, inefficient, and expensive enrichment process driven by necessity:
  - The Aerodynamic process, based on the vortex tube developed and deployed in South Africa, created that country's HEU for nuclear weapons
  - But South Africa's attempted commercialization of this process proved to be uneconomical.
- This case highlights that a nuclear weapons program can provide the initial, substantial capital to develop an enrichment process that is then developed commercially.

Gaseous Diffusion

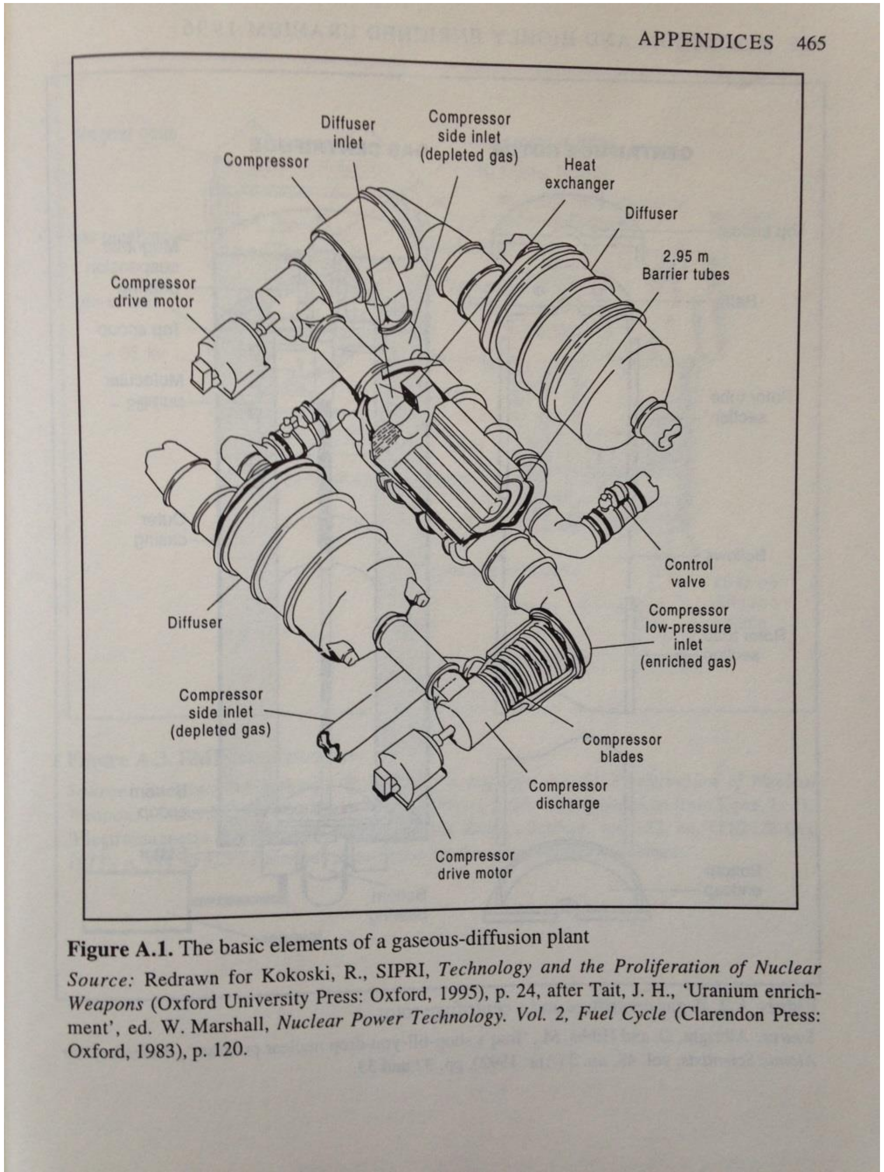
- The gaseous diffusion process was also developed in the Manhattan Project.
- It is inefficient, requires large buildings, and large amounts of electricity to run the equipment.
- But the drive to build nuclear weapons justified the enormous resources devoted to the project.



GASEOUS DIFFUSION PRINCIPLE

- BARRIER IS A POROUS MATERIAL
- LIGHT $^{235}UF_6$ MOLECULES PASS ("DIFFUSE") THROUGH THE BARRIER SLIGHTLY FASTER THAN HEAVY $^{238}UF_6$ MOLECULES

Gaseous Diffusion Components



APPENDICES 465

Figure A.1. The basic elements of a gaseous-diffusion plant

Source: Redrawn for Kokoski, R., SIPRI, *Technology and the Proliferation of Nuclear Weapons* (Oxford University Press: Oxford, 1995), p. 24, after Tait, J. H., 'Uranium enrichment', ed. W. Marshall, *Nuclear Power Technology. Vol. 2, Fuel Cycle* (Clarendon Press: Oxford, 1983), p. 120.

K-25 Gaseous Diffusion Plant

http://blog.nuclearsecrecy.com/wp-content/uploads/2013/05/K25-516.jpg

- The first gaseous diffusion production facility was at Oak Ridge and called the K-25 plant. Built during Manhattan Project, it started making enriched uranium in the summer of 1945 but could not make 80-90 percent enriched uranium until after the war ended.
- But it proved to be more economical than the EMIS plant, which produced its last HEU in 1947.
- K-25 is now long closed, along with the other two gaseous diffusion plants built in the United States

The First Chinese Gaseous Diffusion Plant (labeled “enrichment plant”)

http://belfercenter.hks.harvard.edu/files/INMM-HEU2.pdf

Figure 1: Lanzhou gaseous diffusion plant. Satellite image from 5 July 2004.

Credit: DigitalGlobe and Google Earth.

French Gaseous Diffusion Plant at Tricastin (closed)

http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Conversion-Enrichment-and-Fabrication/Uranium-Enrichment/

Uranium Enrichment (cont.)

- Many other enrichment processes were developed but never deployed on a commercial scale, e.g. the Plasma Separation Process, another aerodynamic process, and Chemical/Ion Exchange.
- So far, laser enrichment of uranium has been uneconomical, even with the emergence of the new SILEX process.
- If deployed commercially, however, SILEX could stimulate a renewed interest in laser enrichment of uranium.

Gas Centrifuges-Next Week

- Gas centrifuges are the other major deployed enrichment process.
- It dominates both the commercial market and the proliferation scene.

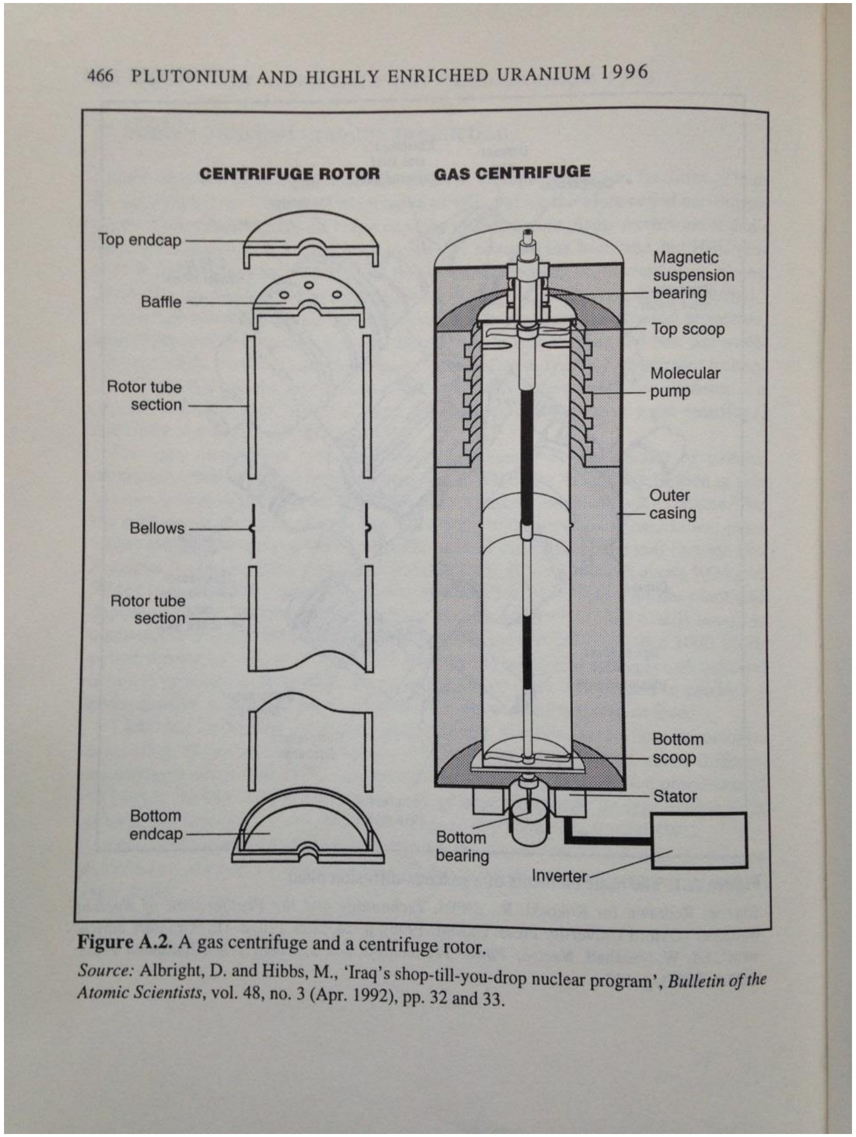


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Figure A.2. A gas centrifuge and a centrifuge rotor.

Source: Albright, D. and Hibbs, M., 'Iraq's shop-till-you-drop nuclear program', *Bulletin of the Atomic Scientists*, vol. 48, no. 3 (Apr. 1992), pp. 32 and 33.