Federal Agency of Higher Education

Tomsk Polytechnic University

Applied Physics and Engineering Faculty

“Uranium enrichment”

Made by:

Student of group 0850

Kiselyova U.V.

.

Tomsk, 2008

1. Uranium Enrichment – Introduction

There is one element that occurs in nature that has been the raw material for nuclear bombs: uranium, chemical symbol U. Uranium occurs in nature as a mixture of three different isotopes – that is, three different atomic weights that have virtually the same chemical properties, but different nuclear properties. These isotopes are U-234, U-235, and U-238. The first is a highly radioactive trace component found in natural uranium, but it is not useful in any applications; the second isotope is the only fissile material that occurs in nature in significant quantities, and the third is the most plentiful isotope (99.284 percent of the weight of a sample of natural uranium is U-238), but it is not fissile. U-238 can, however, be split by high energy neutrons, releasing large amounts of energy and is therefore often used to enhance the explosive power of thermonuclear, or hydrogen, bombs.

Because of the presence of small quantities of U-235, natural uranium can sustain a chain reaction under certain conditions, and therefore can be used as a fuel in certain kinds of reactors (graphite-moderated reactors and heavy water3 reactors, the latter being sold commercially by Canada). For the most common reactor type in use around the world today, which uses ordinary water as a coolant and moderator, the percentage of U-235 in the fuel must be higher than the 0.7 percent found in natural uranium. The set of industrial processes that are used to increase the percentage of U-235 in a given quantity of uranium go under the general rubric of “uranium enrichment” – with the term “enrichment” referring to the increase in the percentage of the fissile isotope U-235. Light water reactors typically use 3 to 5 percent enriched uranium – that is, the proportion of U-235 in the fuel is 3 to 5 percent, with almost all the rest being U-238. Material with this level of U-235 is called “low enriched uranium” or LEU.

Nuclear bombs cannot be made from natural or low enriched uranium. The proportion of U-235, which is the only one of the three isotopes that can sustain a chain reaction in uranium, is just too small to enable a growing “super-critical” chain reaction to be sustained. Uranium must have a minimum of 20 percent U-235 in it in order to be useful in making a nuclear bomb. However, a bomb made with uranium at this minimum level of enrichment would be too huge to deliver, requiring huge amounts of uranium and even larger amounts of conventional explosives in order to compress it into a supercritical mass. In practice, uranium containing at least 90 percent U-235 has been used to make nuclear weapons. Material with this level of enrichment is called highly enriched uranium or HEU. The bomb that destroyed Hiroshima on August 6, 1945, was made with approximately 60 kilograms of HEU. Highly enriched uranium is also used in research reactors and naval reactors, such as those that power aircraft carriers and submarines. The HEU fuel meant for research reactors is considered particularly vulnerable to diversion for use in nuclear weapons.

Thorium-232, which is also naturally occurring, can be used to make bombs by first converting it into U-233 in a nuclear reactor. However, uranium fuel for the reactor, or fuel derived from uranium (such as plutonium) is needed for this conversion if U-233 is to be produced in quantity from thorium-232.

A fissile material is one that can be split (or fissioned) by low energy neutrons and is also capable of sustaining a chain reaction. Only fissile materials may be used as fuel for nuclear reactors or nuclear weapons. Examples of other fissile materials, besides uranium-235, are uranium-233 and plutonium-239.

“Heavy water” is water that contains deuterium in place of the ordinary hydrogen in regular water (also called light water). Deuterium has one proton and one neutron in its nucleus as opposed to hydrogen, which has only a single proton.

The same process and facilities can be used to enrich uranium to fuel commercial light water reactors – that is to make LEU – as well as to make HEU for nuclear bombs. Therefore all uranium enrichment technologies are potential sources of nuclear weapons proliferation. In addition, some approaches to uranium enrichment are more difficult to detect than others, adding to concerns over possible clandestine programs.

2.Uranium Enrichment technologies

Only four technologies have been used on a large scale for enriching uranium. Three of these, gaseous diffusion, gas centrifuges, and jet nozzle / aerodynamic separation, are based on converting uranium into uranium hexafluoride (UF6) gas. The fourth technique, electromagnetic separation, is based on using ionized uranium gas produced from solid uranium tetrachloride (Ucl4).

2.1 Gaseous Diffusion

The gaseous diffusion process has been used to enrich nearly all of the low and highly enriched uranium that has been produced in the United States. It was first developed in the 1940s as part of the Manhattan Project and was used to enrich a portion of the uranium used in the bomb that was dropped on Hiroshima. All five acknowledged nuclear weapons states within the nuclear non-proliferation treaty (NPT) regime have operated gaseous diffusion plants at one time or another, but currently only the United States and France continue to operate such facilities. The diffusion process requires pumping uranium in a gaseous form through a large number of porous barriers and, as noted above, is very energy intensive.

In order to make the uranium into a gaseous form that can be used in the diffusion process, the natural uranium is first converted into uranium hexafluoride (UF6). The uranium hexafluoride molecules containing U-235 atoms, being slightly lighter, will diffuse through each barrier with a slightly higher rate than those containing U-238 atoms. A simple analogy to help visualize this process is to imagine blowing sand through a series of sieves. The smaller grains of sand will preferentially pass through each sieve, and thus after each stage they would represent a slightly higher percentage of the total than they did before passing through the stage. A schematic representation of one such stage from a gaseous diffusion plant is shown in Figure 1.

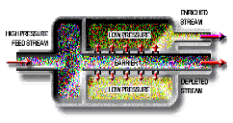


Figure 1: Schematic diagram of a single stage in a gaseous diffusion plant.

The darker colors represent the UF6 molecules that contain the heavier U-238 atoms, while the lighter colors represent gas molecules that contain the lighter U-235. After each stage the gas to the low pressure side of the barrier (i.e. the downstream side) has a slightly higher percentage of U-235 than the stage before.

The difference in mass, and therefore velocity, between the UF6 molecules containing either U-235 or U-238 is very small, and thus thousands of such stages are needed in order to enrich commercial or military amounts of uranium. In a gaseous diffusion plant, the stages are arranged into “cascades” that allow each stage to build on the enrichment achieved by the ones before it and also to more efficiently make use of the depleted uranium stream. For a sense of scale, when it was first constructed in the early 1940s the gaseous diffusion plant at Oak Ridge, Tennessee, was the largest industrial building in the world. The facility at Oak Ridge is shown in Figure 2 while a picture of two of the diffusers used in the enrichment process is shown in Figure 3.



Figure 2: Oak Ridge gaseous diffusion plant, built during World War II.

At the time of its construction this was the largest industrial building in the world. In part it was decided to locate this plant in Tennessee so that its large electricity demand could be met by the abundant coal and hydroelectric plants built by the government run Tennessee Valley Authority. It is now closed and awaiting decommissioning.



Figure 3: A close up picture of the outside of two of the diffuser stages used at the Oak Ridge uranium enrichment plant.

The diffusers contain the porous barriers used to separate the lighter U-235 atoms from the heavier U-238 atoms. Connected to the diffusers is equipment to compress the uranium hexafluoride gas and pipe it through the cascade as well as equipment to remove the large amount of heat generated during the enrichment process. Each diffuser and compressor are together referred to as a “stage.”

The most challenging step in building a gas diffusion plant is to manufacture the permeable barriers required in the diffusers. The material for the barriers needs to be highly durable and able to maintain a consistent pore diameter for several years of operation. This is particularly challenging given the highly corrosive nature of the uranium hexafluoride gas used. Typical barriers are just 5 millimeters (less than 0.2 inches) thick and have openings that are only about 30 to 300 times the diameter of a single uranium atom.

In addition to requiring a large amount of electricity during operation, the compressors in the gas diffusion facilities also generate a great deal of heat that requires dissipation. In U.S. plants this heat is dissipated through the use of ozone depleting chlorofluorocarbons (CFCs) such as the coolant CFC-114 (often referred to simply as Freon of Freon-114). The manufacture, import, and use of CFCs were substantially restricted by the 1987 Montreal Protocol on Substances That Deplete the Ozone Layer, which the U.S. is implementing through the 1990 Amendments to the Clean Air Act. As a result of these commitments, the manufacture of Freon in the U.S. ended in 1995 and its emissions to the air in the United States from large users fell by nearly 60% between 1991 and 2002.The emissions from the Paducah gaseous diffusion plant, however, have remained virtually constant over this time, falling just over 7% between 1989 and 2002.In 2002, the Paducah enrichment plant emitted more than 197.3 metric tons of Freon into the air through leaking pipes and other equipment. This single facility accounted for more than 55% of all airborne releases of this ozone depleting CFC from all large users in the entire United States in 2002.Due to the lack of additional manufacturing of Freon since 1995, the U.S. Enrichment Corporation is currently looking for a non-CFC coolant to use. Likely candidates would still have heat trapping potential, and thus even if they were not as dangerous to the ozone layer, they would still remain a potential concern in relation to global warming and climate change.

The high heat signature of gaseous diffusion plants makes it possible that plants operating significantly in excess of 100 MTSWU per year could be detected. However, this information would likely only be meaningful as a way of identifying operations at known plants and not for uncovering clandestine facilities since there are many industrial processes that generate a great deal of heat. Thus, while gaseous diffusion plants are perhaps one of the hardest types of uranium enrichment facility to hide given their size, electricity needs, and heat signature, it would still be difficult to remotely identify a facility without access to environmental samples from the surrounding area.

2.2 Gas Centrifuge

Gas centrifuges are the most commonly used technology today for enriching uranium. The technology was considered in the U.S. during the Manhattan Project, but gaseous diffusion and electromagnetic separation were pursued instead for full scale production. The centrifuge was later developed in Russia by a team lead by Austrian and German scientists captured during the Second World War. The head of the experimentation group in Russia was eventually released and took the centrifuge technology first to the United States and then to Europe where he sought to develop its use in enriching commercial nuclear fuel.

The centrifuge is a common technology used routinely in a variety of applications such as separating blood plasma from the heavier red blood cells. In the enrichment process, uranium hexafluoride gas is fed into rapidly spinning cylinders. In order to achieve as much enrichment in each stage as possible, modern centrifuges can rotate at speeds approaching the speed of sound. It is this feature that makes the centrifuge process difficult to master, since the high rate of revolution requires that the centrifuge be sturdy, nearly perfectly balanced, and capable of operating in such a state for many years without maintenance. Inside the rotating centrifuge, the heavier molecules containing U-238 atoms move preferentially towards the outside of the cylinder, while the lighter molecules containing U-235 remain closer to the central axis. The gas in this cylinder is then made to circulate bottom to top driving the depleted uranium near the outer wall towards the top while the gas enriched in U-235 near the center is driven towards the bottom. These two streams (one enriched and one depleted) can then be extracted from the centrifuge and fed to adjoining stages to form a cascade just as was done with the diffusers in the gas diffusion plants. A schematic diagram of such a centrifuge is shown in Figure 4 below.



Figure 4: A schematic diagram of the cross section of a single gas centrifuge.

The rotating cylinder forces the heavier U-238 atoms towards the outside of the centrifuge while leaving the lighter U-235 more towards the middle. A bottom to top current allows the enriched and depleted streams to be separated and sent via pipes to subsequent stages. Like the gas diffusion process, it requires thousands to tens of thousands of centrifuge stages to enrich commercially or militarily significant quantities of uranium. In addition, like the gas diffusion plants, centrifuge plants require the use of special materials to prevent corrosion by the uranium hexafluoride, which can react with moisture to form a gas of highly corrosive hydrofluoric acid. One of the most important advantages to the gas centrifuge over the gas diffusion process, however, is that it requires 40 to 50 times less energy to achieve the same level of enrichment. The use of centrifuges also reduces the amount of waste heat generated in compressing the gaseous UF6, and thus reduces the amount of coolants, such as Freon, that would be required. A bank of centrifuges from an enrichment plant in use in Europe is shown in Figure 5.



Figure 5: A section of a typical cascade of centrifuge stages in a European uranium enrichment plant. The operative power of each centrifuge increases with the speed of revolution as well as with the height of the centrifuge while in a cascade each centrifuge also builds on the enrichment achieved in the previous stages.

Despite having a larger operative power in each stage compared to the gaseous diffusion process, the amount of uranium that can pass through each centrifuge stage in a given time is typically much smaller. Typical modern centrifuges can achieve approximately 2 to 4 SWU annually, and therefore in order to enrich enough HEU in one year to manufacture a nuclear weapon like that dropped on Hiroshima would require between three and seven thousand centrifuges. Such a facility would consume 580 to 816 thousand kWh of electricity, which could be supplied by less than a 100 kilowatt power plant. The use of modern weapon designs would reduce those numbers to just one to three thousand stages and 193 to 340 thousand kWh. More advanced centrifuge designs are expected to achieve up to ten times the enrichment per stage as current models which would further cut down on the number necessary for the clandestine production of HEU. The reported sale of older European based centrifuge technology to countries like Libya, Iran, and North Korea from the network run by A.Q. Khan, the former head of the Pakistani nuclear weapons program, highlights the concerns over the smaller size and power needs of the centrifuge enrichment process from a proliferation standpoint.

2.3 Electromagnetic Isotope Separation (EMIS)

The electromagnetic separation technique is a third type of uranium enrichment process that has been used in the past on a large scale. Developed during the Manhattan Project at Oak Ridge, Tennessee, the electromagnetic separation plant was used to both enrich natural uranium as well as to further enrich uranium that had been initially processed through the gaseous diffusion plant, which was also located at the Oak Ridge facility. The use of this type of facility, shown in Figure 6, was discontinued shortly after the war because it was found to be very expensive and inefficient to operate. Iraq did pursue this technique in the 1980s as part of their effort to produce HEU, because of its relative simplicity in construction, but they were only successful in producing small amounts of medium enriched uranium (just above 20 percent).



Figure 6: The electromagnetic separations plant built at Oak Ridge, Tennessee during the Manhattan Project. These devices, also referred to as cauldrons, were used in enriching a part of the uranium for the bomb that was dropped by the United States on Hiroshima.

The electromagnetic separations process is based on the fact that a charged particle moving in a magnetic field will follow a curved path with the radius of that path dependent on the mass of the particle. The heavier particles will follow a wider circle than lighter ones assuming they have the same charge and are traveling at the same speed. In the enrichment process, uranium tetrachloride is ionized into a uranium plasma (i.e. the solid Ucl4 is heated to form a gas and then bombarded with electrons to produce free atoms of uranium that have lost an electron and are thus positively charged). The uranium ions are then accelerated and passed through a strong magnetic field. After traveling along half of a circle (see Figure 6) the beam is split into a region nearer the outside wall which is depleted and a region nearer the inside wall which is enriched in U-235. The large amounts of energy required in maintaining the strong magnetic fields as well as the low recovery rates of the uranium feed material and slower more inconvenient facility operation make this an unlikely choice for large scale enrichment plants, particularly in light of the highly developed gas centrifuge designs that are employed today.

2.4 Jet Nozzle / Aerodynamic Separation

The final type of uranium enrichment process that has been used on a large scale is aerodynamic separation. This technology was developed first in Germany and employed by the apartheid South African government in a facility which was supposedly built to supply low enriched uranium to their commercial nuclear power plants as well as some quantity of highly enriched uranium for a research reactor. In reality, the enrichment plant also supplied an estimated 400 kg of uranium enriched to greater than 80% for military use.In early 1990, President de Klerk ordered the end of all military nuclear activities and the destruction of all existing bombs. This was completed roughly a year and a half later, just after South Africa joined the NPT regime and just before submitting to inspections and safeguards by the International Atomic Energy Agency.

The aerodynamic isotope separation (which includes the jet nozzle and helicon processes) achieves enrichment in a manner similar to that employed with gas centrifuges in the sense that gas is forced along a curved path which moves the heavier molecules containing U-238 towards the outer wall while the lighter molecules remain closer to the inside track. In the jet nozzle plants, uranium hexafluoride gas is pressurized with either helium or hydrogen gas in order to increase the velocity of the gas stream and the mixture is then sent through a large number of small circular pipes which separate the inner enriched stream from the outer depleted stream. This process is one of the least economical enrichment techniques of those that have been pursued, given the technical difficulties in manufacturing the separation nozzles and the large energy requirements to compress the UF6 and carrier gas mixture. As with gaseous diffusion plants, there is a large amount of heat generated during operation of an aerodynamic separations plant which requires large amounts of coolants such as Freon.

2.5 Other Technologies

There are a number of other uranium enrichment technologies such as atomic vapor laser isotope separation (AVLIS), molecular laser isotope separation (MLIS), chemical reaction by isotope selective laser activation (CRISLA), and chemical and ion exchange enrichment that have been developed as well, but they are mostly still in the experimental or demonstration stage and have not yet been used to enrich commercial or military quantities of uranium. The AVLIS, CRISLA, and MLIS processes make use of the slight difference in atomic properties of U-235 and U-238 to allow powerful lasers to preferentially excite or ionize one isotope over the other. AVLIS makes use of uranium metal as a feed material and electric fields to separate the positively charged U-235 ions from the neutral U-238 atoms. MLIS and CRISLA on the other hand use uranium hexafluoride mixed with other process gases as a feed material and use two different lasers to excite and then chemically alter the uranium hexafluoride molecules containing U-235, which can then be separated from those molecules containing U-238 that remained unaffected by the lasers. AVLIS was pursued for commercial use by the U.S. Enrichment Corporation, but was abandoned in the late 1990s as being unprofitable while other countries have also abandoned all known AVLIS and MLIS production programs as well. The chemical and ion exchange enrichment processes were developed by the French and the Japanese. These techniques make use of the very slight differences in the reaction chemistry of the U-235 and U-238 atoms. Through the use of appropriate solvents, the uranium can be separated into an enriched section (contained in one solvent stream) and a depleted stream (contained in a different solvent that does not mix with the first in the same way that oil and water do not mix). This enrichment technique was also pursued by Iraq. Currently all known programs involving this technique have been closed since at least the early 1990s. All of these technologies have been demonstrated on the small scale and some, like AVLIS, have gone further along in the development process that would be necessary to scale up to production level facilities. This would be particularly true if the profitability of the plant was not an issue and it was only meant to enrich the reasonably modest quantities of HEU necessary for one to two bombs per year. Currently, however, the gas centrifuge appears to be the primary technology of choice for both future commercial enrichment as well as for potential nuclear weapons proliferation.

Reference List

1. David Albright, Frans Berkhout and William Walker. “Plutonium and Highly Enriched Uranium 1996”. Stockholm, 1997.
2. Laughter, Mark D. (2007) “Profile of World Uranium Enrichment Programs – 2007”. ORNL/TM – 2007/193
3. David Albright “Irag’s Programs toMake Highly Enriched Uranium and Plutonium for Nuclear Weapons Prior to the Gulf War”, 2002
4. Nuclear Engineering International. 2004 World Nuclear Industry Handbook. Wilmington Pub. Co., 2004