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URANIUM ENRICHMENT

Just Plain Facts to Fuel an Informed Debate on Nuclear Proliferation and Nuclear Power

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Prepared by

Institute for Energy and Environmental Research

for the

Nuclear Policy Research Institute

15 October 2004

Reprinted, with revisions and minor corrections, March 2005.
Revisions to the original text can be found on the Web at http://www.ieer.org/errata.html.

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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.[1] 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 (see Appendix 1: Uranium: Its Uses and Hazards). 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[2] 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 water[3] 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.

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[1] 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.

[2] 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.

[3] "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 and Depleted Uranium – Basics: Science

Since all isotopes of uranium have virtually the same chemical properties[4], increasing the proportion of uranium in a sample depends on the difference in atomic weights of the isotopes (represented by the numbers 234, 235, and 238 attached to them). U-238 is a little over 1 percent heavier than U-235. If uranium can be put into a gaseous form, then the molecules containing the lighter U-235 will have a greater speed on average (at a given temperature) than the heavier ones containing U-238. During the typical enrichment processes, a stream of natural uranium which has been converted into a gas containing both U-235 and U-238 is split up into two streams by making use of the slight difference in mass of the two isotopes. One of the streams is richer in U-235 (the "enriched" uranium stream) while the other is poorer in U-235 (the "depleted" uranium stream – the term depleted refers to a lower percentage of U-235 relative to natural uranium).

The capacity of a uranium enrichment facility to increase the percentage of U-235 is given by a unit known as the kilogram Separative Work Unit (SWU). Production level facilities typically have a capacity that range from a few hundred to several thousand metric tons SWU (MTSWU = 1,000 SWU). The Separative Work Unit is a complex unit that depends upon both the percentage of U-235 that is desired in the enriched stream and how much of the U-235 in the feed material ends up in the depleted uranium stream. The SWU unit can be thought of as the amount of effort that is required to achieve a given level of enrichment. The less U-235 in the feed material that is allowed to end up in the depleted uranium, the greater the number of SWUs required to achieve the desired level of enrichment. The number of Separative Work Units provided by an enrichment facility is directly related to the amount of energy that the facility consumes. The two most important enrichment technologies in use today (described in greater detail below) differ greatly in their energy needs. Modern gaseous diffusion plants typically require 2,400 to 2,500 kilowatt-hours of electricity per SWU while gas centrifuge plants require just 50 to 60 kilowatt-hours of electricity per SWU.

In addition to the Separative Work Units provided by an enrichment facility, the other important parameter that must be considered is the mass of natural uranium that is needed in to order to yield a desired mass of enriched uranium. As with the number of SWUs, the amount of feed material required will also depend on the level of enrichment desired and upon the amount of U-235 that ends up in the depleted uranium. However, unlike the number of SWUs required during enrichment which increases with decreasing levels of U-235 in the depleted stream, the amount of natural uranium needed will decrease with decreasing levels of U-235 that end up in the depleted uranium.

[4] There is one type of enrichment process that does make use of the very small differences between the isotopes' chemical properties to separate U-235 from U-238. The so-called chemical and ion exchange enrichment process is described in more detail on page 13.

For example, in the enrichment of LEU for use in a light water reactor it is typical for the enriched stream to contain 3.6% U-235 (as compared to 0.7% in natural uranium) while the depleted stream contains 0.2% to 0.3% U-235. In order to produce one kilogram of this low enriched uranium it would require approximately 8 kilograms of natural uranium and 4.5 SWU if the depleted uranium stream was allowed to have 0.3% U-235. On the other hand, if the depleted stream had only 0.2% U-235, then it would require just 6.7 kilograms of natural uranium, but nearly 5.7 SWU of enrichment. Because the amount of natural uranium required and the number of SWUs required during enrichment change in opposite directions, if natural uranium is cheap and enrichment services are relatively more expensive, then the operators will typically choose to allow more U-235 to be "wasted" in the depleted uranium stream whereas if natural uranium is relatively more expensive and enrichment is less so, then they would choose the opposite.

In order to provide the enriched uranium required to fuel a typical light water reactor with a capacity of 1,000 megawatts electric, it would take approximately 100,000 to 120,000 SWU a year of enrichment services. If this enrichment was provided by a gaseous diffusion plant (as is currently operated in the United States at Paducah, Kentucky) then the enrichment process would consume roughly 3 to 4 percent of the electricity generated by the reactor.[5] On the other hand, if the uranium fuel was enriched in gas centrifuges (as are currently operated in many parts of the world) then the enrichment process would consume less than 0.1% of the electricity generated by the nuclear plant during the year.

For comparison to these requirements for producing low enriched uranium for reactor fuel, in order to produce one kilogram of highly enriched uranium (i.e. uranium containing 90% U-235) it would require more than 193 SWU and nearly 219 kilograms of natural uranium if the depleted uranium contained 0.3% U-235. On the other hand, it would require nearly 228 SWU and more than 176 kilograms of natural uranium if the depleted stream contained 0.2% U-235. In other words, in order to enrich enough uranium to build a bomb like the one that was dropped by the United States on Hiroshima (approximately 60 kg of HEU), it would require between 10.6 and 13.1 metric tons of natural uranium and 11,600 to 13,600 SWU of enrichment. More sophisticated nuclear weapons designs, however, would require significantly less than half that amount. It is typical for modern uranium bombs to require just 20 to 25 kilograms of HEU.

Adding to the proliferation concerns regarding the spread of enrichment technologies as part of the spread of nuclear power, it is important to note that if, instead of starting with natural uranium, low enriched uranium (3.6% U-235) was used as the feed material, then it would require just 70 to 78 SWU and 26 to 27 kilograms of feed material to produce one kilogram of highly enriched uranium. Just 1.6 tons of LEU, less than one tenth of the amount needed annually to fuel a single 1000 megawatt reactor, would be enough to yield the HEU required to assemble a Hiroshima style bomb if it was further enriched. Thus, stockpiles of low enriched uranium, if maintained in a form suitable for enrichment, can provide the base material to more easily and more rapidly manufacture highly enriched uranium for use in nuclear weapons. In this example, approximately two-thirds of the total enrichment services necessary to produce weapons usable HEU goes into enriching the uranium from natural uranium (0.7% U-235) to LEU (3.6% U-235) while only about one-third goes into enriching the LEU the rest of the way from 3.6% U-235 to HEU with 90% U-235.

[5] This calculations assumes that the nuclear plant operates at full power for approximately 80 to 90 percent of the year.

3. 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 (UF_6) gas. The fourth technique, electromagnetic separation, is based on using ionized uranium gas produced from solid uranium tetrachloride (UCl_4).

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 (UF_6). 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.

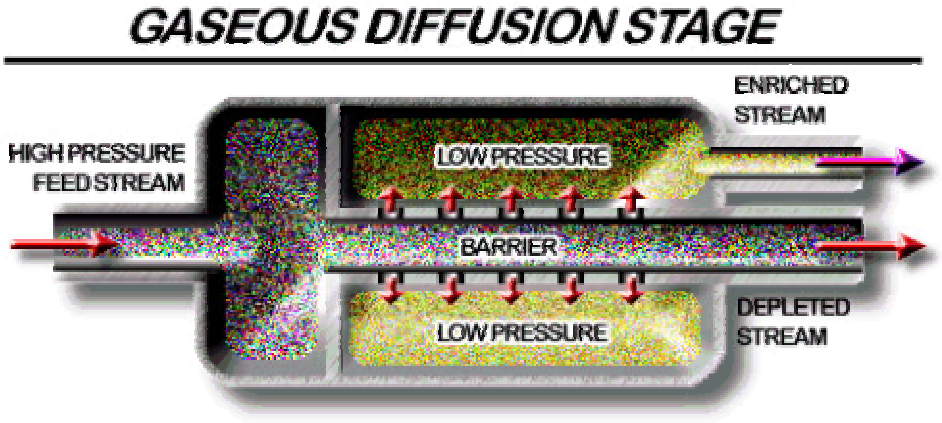

Figure 1: Schematic diagram of a single stage in a gaseous diffusion plant. The darker colors represent the UF_6 molecules that contain the heavier U-238 atoms, while the lighter colors represent gas molecules that contain the lighter U-235. After each stage the gas to the low pressure side of the barrier (i.e. the downstream side) has a slightly higher percentage of U-235 than the stage before. (Image courtesy of USEC Inc, http://www.usec.com/v2001_02/HTML/Aboutusec_enrichment.asp.)

The difference in mass, and therefore velocity, between the UF_6 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.

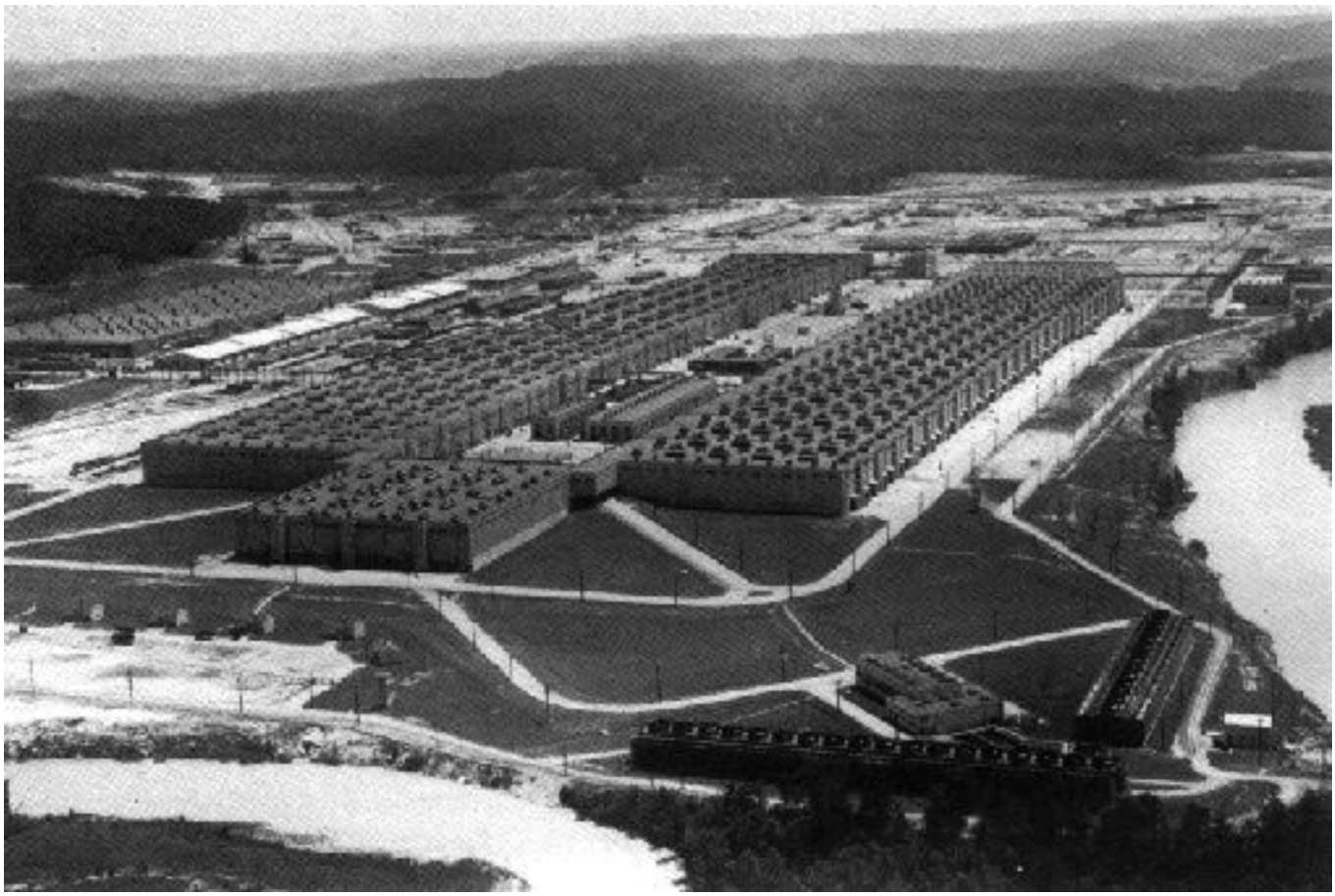

Figure 2: Oak Ridge gaseous diffusion plant, built during World War II. At the time of its construction this was the largest industrial building in the world. In part it was decided to locate this plant in Tennessee so that its large electricity demand could be met by the abundant coal and hydroelectric plants built by the government run Tennessee Valley Authority. It is now closed and awaiting decommissioning. (photo taken from the website of the "Scientific History of the Atomic Bomb" online at http://www.hcc.mnscu.edu/programs/dept/chem/abomb/K25_Aerial.jpg)

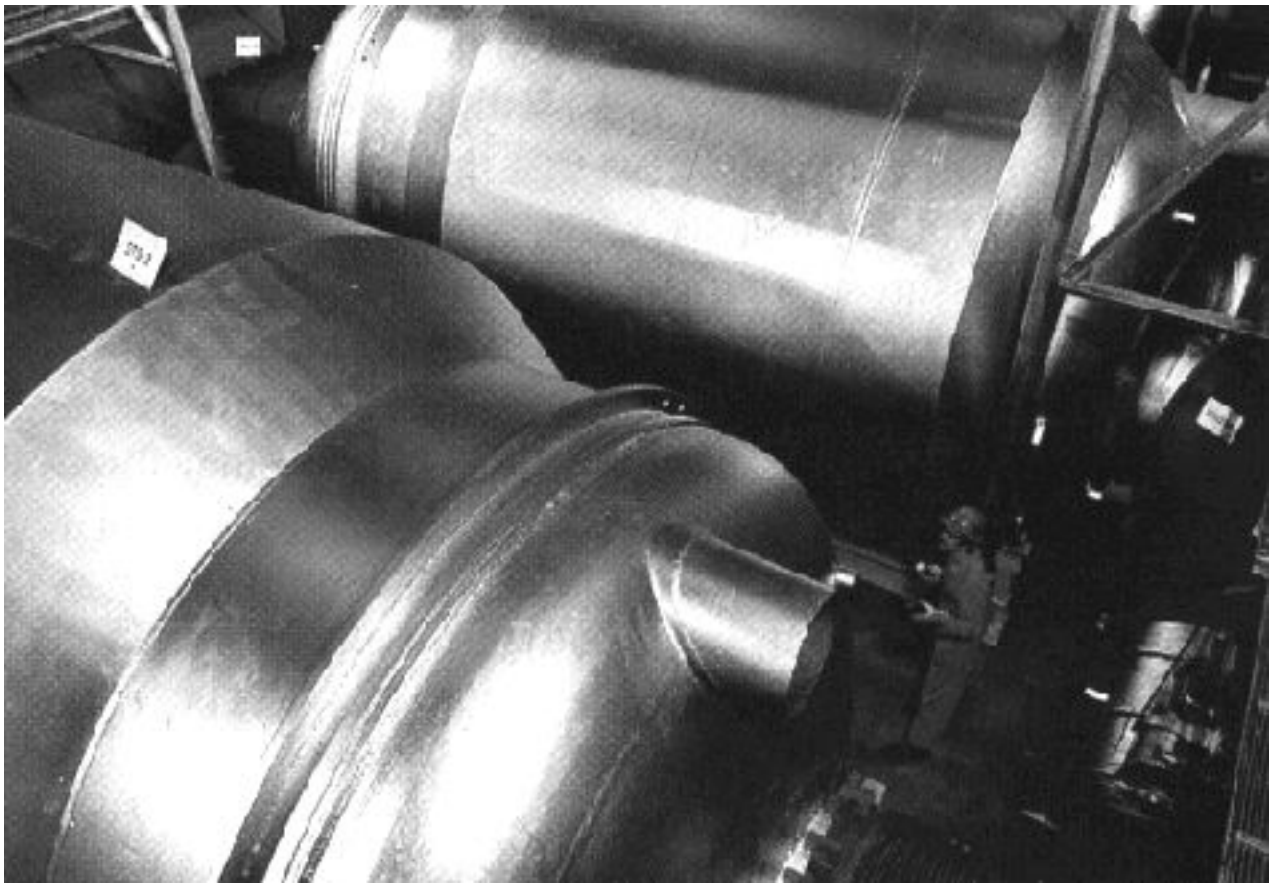

Figure 3: A close up picture of the outside of two of the diffuser stages used at the Oak Ridge uranium enrichment plant. The diffusers contain the porous barriers used to separate the lighter U-235 atoms from the heavier U-238 atoms. Connected to the diffusers is equipment to compress the uranium hexafluoride 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." (photo taken from the website of the "Scientific History of the Atomic Bomb" online at http://www.hcc.mnscu.edu/programs/dept/chem/abomb/Diffusers.jpg)

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.[6]

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

[6] NRC 2003

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.[7] The emissions from the Paducah gaseous diffusion plant, however, have remained virtually constant over this time, falling just over 7% between 1989 and 2002.[8] 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.[9] 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.

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.[10]

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

[7] EPA 2004
[8] DOE/EIA 1994 in Chapter 5 and USEC 2003 p. 8
[9] USEC 2003 p. 8 and EPA 2004
[10] Broad 2004

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.

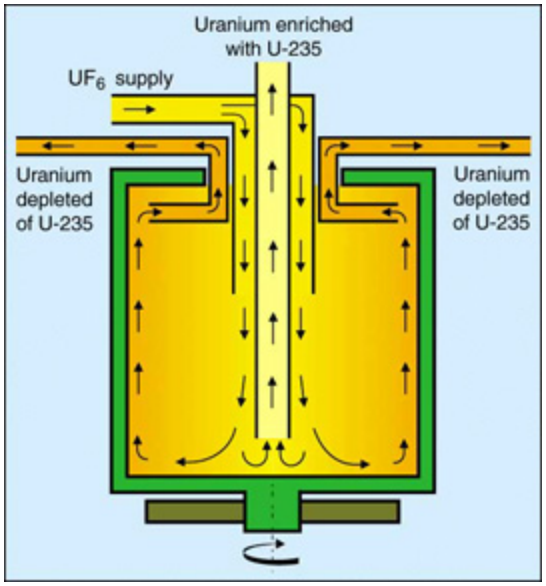

Figure 4: A schematic diagram of the cross section of a single gas centrifuge. The rotating cylinder forces the heavier U-238 atoms towards the outside of the centrifuge while leaving the lighter U-235 more towards the middle. A bottom to top current allows the enriched and depleted streams to be separated and sent via pipes to subsequent stages. (image taken from the website of the European Nuclear Society online at http://www.euronuclear.org/info/encyclopedia/images/gascentrifuge.jpg)

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 UF_6, 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.

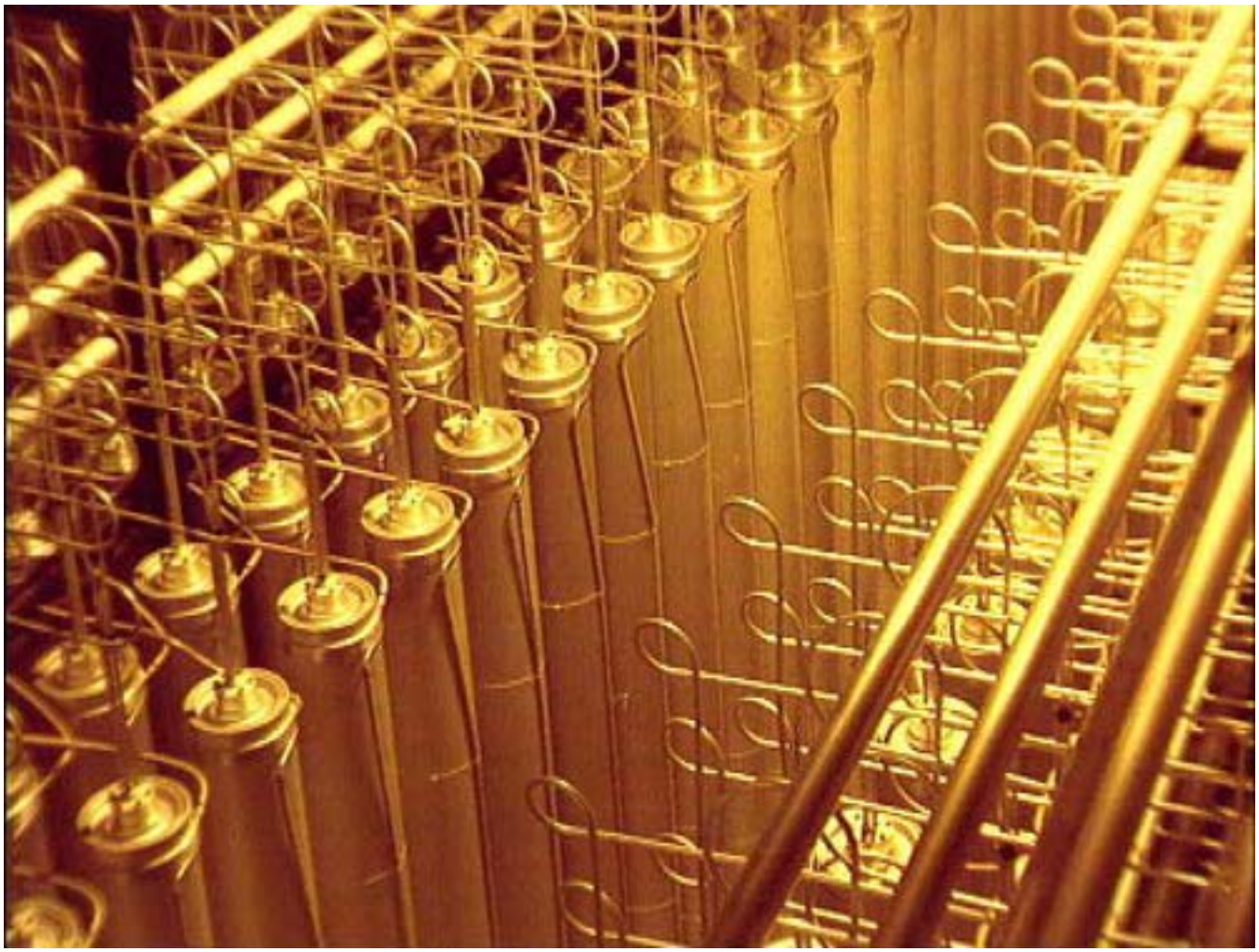

Figure 5: A section of a typical cascade of centrifuge stages in a European uranium enrichment plant. The separative power of each centrifuge increases with the speed of revolution as well as with the height of the centrifuge while in a cascade each centrifuge also builds on the enrichment achieved in the previous stages. (photo taken from the Uranium Information Centre online at http://www.uic.com.au/graphics/centrfge.jpg)

Despite having a larger separative 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.[11]

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).[12]

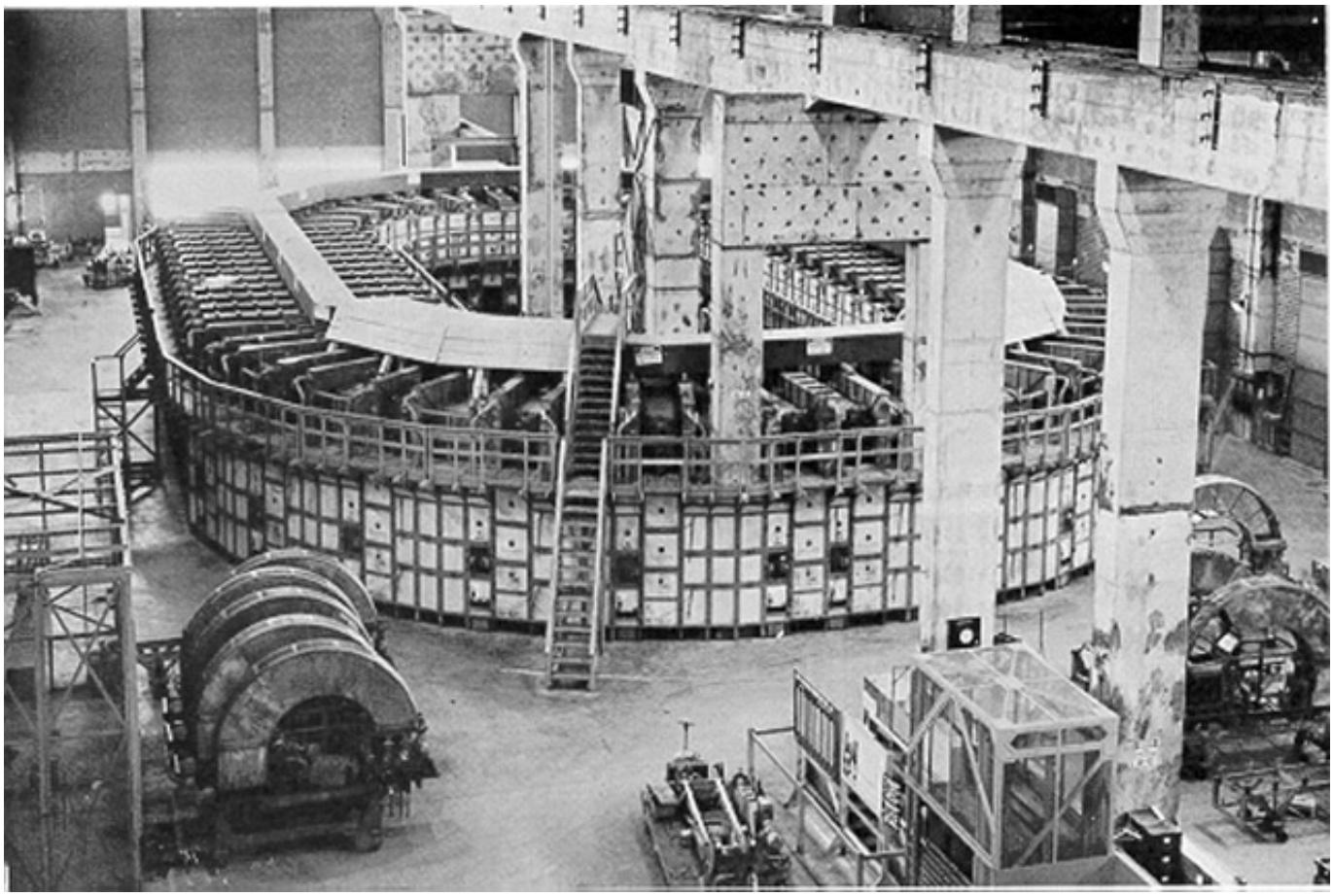

Figure 6: The electromagnetic separations plant built at Oak Ridge, Tennessee during the Manhattan Project. These devices, also referred to as calutrons, were used in enriching a part of the uranium for the bomb that was dropped by the United States on Hiroshima. (photo taken from the website of The Manhattan Project Heritage Preservation Association online at http://www.childrenofthemanhattanproject.org/OR/Photo-Pages/ORP-149.htm)

[11] White House 2004
[12] Albright 2002

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 UCl_4 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.

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.[13] 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.[14]

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 UF_6 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.

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.

[13] Albright 1994 p. 40
[14] Albright 1994 p. 46-47

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.

4. Uranium Enrichment – the present situation

All five nuclear weapons states that are parties to the nuclear non-proliferation treaty (NPT) – the United States, Russia, Britain, France, and China – have uranium enrichment plants that have been used to create HEU for weapons. All five of these countries also have uranium enrichment facilities that have been used for producing LEU for commercial power reactor fuel. Pakistan, one of the countries known to have produced nuclear weapons outside the NPT regime, has facilities that have enriched HEU for military applications. India and Israel on the other hand have produced nuclear bombs from plutonium-239 (which is made in nuclear reactors when the non-fissile U-238 captures a low energy neutron).[15]

Table 1 shows the weapons programs of these eight countries and their relation to uranium enrichment. All of them either have uranium enrichment plants or some ambitions in that direction, and all but two have manufactured nuclear weapons incorporating highly enriched uranium. It is important to keep this in mind when considering who is trying to stop whom from getting what in relation to nuclear technologies.

[15] North Korea withdrew from the NPT in December 2003 without providing the required 3 month notification. They are estimated to have produced a small number of nuclear weapons using plutonium.

Table 1: Nuclear Weapons States - Uranium Enrichment, Military and Commercial

Country	Weapons Program Material	Commercial Uranium Enrichment	Comments
United States	Pu, HEU	Yes	full scale production plants
Russia	Pu, HEU	Yes	full scale production plants
Britain	Pu, HEU	Yes	full scale production plants
France	Pu, HEU	Yes	full scale production plants
China	Pu, HEU	Yes	full scale production plants
Israel	Pu	No	experimental enrichment program
India	Pu	No	experimental enrichment program
Pakistan	HEU	No	full scale production plant

Table 2 summarizes the current information that is available regarding the state of uranium enrichment facilities around the world. It is separated by country and includes what type of process the plant utilizes, what its enrichment capacity is (as measured by MTSWU per year), what its current operational status is, as well as other information. There are two important limitations to this information, however, that should be kept in mind when examining this table. The first thing is that this table includes only those facilities that are known about from either international safeguard agreements or information published or released by the countries or by someone within the country. This is perhaps a tautology, but it is important to consider given the potential for clandestine facilities (particularly gas centrifuge plants). The recent experience with the revelations surrounding the A.Q. Khan network provide one very significant example of illicit proliferation of enrichment technology, conducted at least in part by private individuals.

The second important limitation is that, even for the known facilities, there is often conflicting and contradictory information available regarding their current status, their capacity, and even sometimes their location. When possible the conflicts in information are touched on in Table 2, however, this was not possible for the individual plant capacities. Typically the reported differences in plant capacities were not significantly different between sources and therefore the information presented is, in fact, representative of the estimated production capacity of the listed facilities. Laboratory scale programs are difficult to detect or monitor and it is likely that some countries not listed in Table 2 have pursued enrichment or other isotope separation experiments. The information primarily relied upon to construct Table 2 was compiled by the International Atomic Energy Agency as well as by a number of security related non-governmental organizations whom we would like to acknowledge for their significant work in these areas.

Table 2: URANIUM ENRICHMENT WORLDWIDE

By groups:

- **Declared nuclear weapons states: China, France, Russia, United Kingdom, United States**
- **Nuclear weapons states, not signatories of the NPT: India, Israel, Pakistan**
- **States of concern to U.S.: Iran, Iraq, North Korea**
- **Additional states: Not suspected of having weapons ambitions at this time**: **Argentina, Australia, Brazil, Germany, Japan, Netherlands, South Africa, South Korea**

Location	Process/ Scale[1]	Dates	Nominal capacity	Comments
Declared Nuclear Weapons states: China, France, Russia, United Kingdom, United States				
China[23]				
Lanzhou 1, Lanzhou Nuclear Fuel Complex (LNFC), Gansu province	Gaseous diffusion/ Commercial	Startup 1980. Shutdown 1997. Decommis-sioning started in 1999	900 MTSWU/a	Source: IAEA NFCIS 2000. Owned & operated by: China National Nuclear Corporation (CNNC)
Lanzhou 2, Lanzhou Nuclear Fuel Complex (LNFC), Gansu province.	Centrifuge/ Commercial	Under construction[4]	500 MTSWU/a	Source: IAEA NFCIS 2000. Owned by: China National Nuclear Corporation (CNNC). The plant under construction constitutes Phase 3 of the development of commercial centrifuge plants. A fourth phase will create another plant.[5]
Heping, Sichuan	Gaseous diffusion/ Commercial	Date of completion: 1970's	>200 MTSWU/a	Source: Albright, Berkhout & Walker 1997, p. 471, 127-128.
Hanzhong, Shaanxi Province[6]	Centrifuge/ Commercial	Startup 1996 and 1998, for plants 1 & 2 respectively[7]	500 MTSWU/a	NTI China 2003. Owned by, China National Nuclear Corporation (CNNC). The two plants constructed here constitute Phases 1 & 2 of the development of commercial centrifuge plants.[8]
China Institute of Atomic Energy, Tuoli, near Bejing	Gaseous diffusion/ Laboratory	Not given	Not given	Source: CEIP 2002, p. 160.
Fudan University, Shanghai	CRISLA[9]/ Not given	Not given	Not given	Source: NTI China 2003.
Xian, Shaanxi Province[10]	Not given	Not given	Not given	Source: NTI China 2003.
France[11]				
Georges Besse, Tricastin[12], Drome[13]	Gaseous diffusion/ Commercial	Startup 1979	10,800 MTSWU/a	Source: IAEA NFCIS 2003. Owned by Eurodif.[14]

Georges Besse II, Tricastin, Drome[15]	Centrifuge/ Commercial	Planned	7,500 MTSWU/a	Source: IAEA NFCIS 2003. Owned & operated by COGEMA. See also http://www.cogema.fr/index_gb.html
Pierrelatte - UB-UM-UH-UTH, Pierrelante, Drome	Gaseous diffusion/ Commercial	Startup 1964; Shutdown 1982. Decommissio n-ing.	0 MTSWU/a (as given by IAEA)	Source: IAEA NFCIS 2000. Owned by Commissariat a l'energie atomique (CEA).
PL4, Grenoble, Isere	Chemical Exchange /Pilot Plant	Startup 1986; Shut down 1988.	0 MTSWU/a (as given by IAEA)	Source: IAEA NFCIS 1999. Owned & operated by Commissariat a l'energie atomique (CEA).
Saclay - ASTER, Saclay, Essonne	Laser (SILVA)[16]/ Laboratory	Startup 1988. Shutdown 2003[17]	0 MTSWU/a (as given by IAEA)	Source: IAEA NFCIS 2001. Owned & operated by Commissariat a l'energie atomique (CEA).
Pierrelatte - P (Laser), Pierrelante, Drome	Laser (AVLIS)/[18] Laboratory	Under study 1977[19]	0 MTSWU/a (as given by IAEA)	Source: IAEA NFCIS 2001. Owned & operated by Commissariat a l'energie atomique (CEA). A SILVA pilot project at Pierrelatte, called Menphis, was "completed…in early 2003. In November [2003] the CEA conducted a demonstration production run in the pilot…" (Davis English).[20]
Russia[21]				
Ekaterinburg,[22] Sverdlovsk, Sverdlovskaya Oblast.[23]	Centrifuge/ Commercial[24]	Startup 1949	7,000 MTSWU/a	Source: IAEA NFCIS 2003. Owned by Ministry of Atomic Energy (MINATOM). Operated by Ural Electrochemical Integrated Plant.
Siberian Chemical Combine (Seversk)[25], Tomsk, Tomskaya Oblast[26]	Centrifuge/ Commercial[27]	Start up 1950	4,000 MTSWU/a	Source: IAEA NFCIS 2003. Owned & operated by Ministry of Atomic Energy (MINATOM)
Krasnoyarsk,[28] Krasnoyarskaya Oblast[29]	Centrifuge/ Commercial	Startup 1964	3,000 MTSWU/a	Source: IAEA NFCIS 2003. Owned by Ministry of Atomic Energy (MINATOM) Operated by MINATOM (TENEX)
Angarsk, Irkutskaya Oblast[30]	Centrifuge/ Commercial	Startup 1954	1,000 MTSWU/a	Source: IAEA NFCIS 2003. Owned & operated by Ministry of Atomic Energy (MINATOM)

United Kingdom[31]				
Urenco Capenhurst, Cheshire[32]	Centrifuge/ Commercial	Startup 1972	2,300 MTSWU/a [33]	Source: IAEA NFCIS 2003 . Owned by URENCO Enrichment Co Ltd; operated by URENCO (Capenhurst) Ltd.[34]
BNFL Capenhurst (GD), Capenhusrt, Cheshire	Gaseous diffusion/ Commercial	Startup 1953; Shutdown 1982. Decommis-sioned.	350 MTSWU/a	Source: IAEA NFCIS 2003. Owned & operated by British Nuclear Fuels PLC.
United States				
Paducah Gaseous Diffusion Paducah, Kentucky[35]	Gaseous diffusion/ Commercial	Startup 1954[36]	11,300 MTSWU/a	Source: IAEA NFCIS 2003. Owned by U.S. Dept. of Energy (DOE). Operated by USEC Inc.
Portsmouth Gaseous Diffusion, Portsmouth (or Piketon), Ohio	Gaseous diffusion/ Commercial	Startup 1956.[37] Shutdown 2001. Now on stand by[38]	7,400 MTSWU/a	Source: IAEA NFCIS 2003. Owned by U.S. Dept. of Energy (DOE). Operated by USEC Inc.
Oak Ridge K-25, Y-12, Oak Ridge, Tennessee	Gaseous diffusion/ Commercial	Startup 1945; Shutdown 1985	8,500 MTSWU/a	Source: IAEA NFCIS 2003. Owned by U.S. Dept. of Energy (DOE). Operated by Exxon Coal and Minerals Company.
American Centrifuge Commercial Plant, Portsmouth (or Piketon), Ohio	Centrifuge/ Commercial	Planned.[39]	3,500 MTSWU/a by 2010	Source: USEC Fact Sheet Piketon. Operated by USEC Inc. Agreements between DOE and USEC will "allow USEC to further develop DOE's gas centrifuge technology"and lease the buildings at Piketon (NRC FAQ Centrifuges 2004).
Louisiana Energy Services Gas Centrifuge Facility, Eunice, New Mexico	Centrifuge/ Commercial	Proposed. Projected for 2010 or 2011	3,000 MTSWU/a	Source: NRC LES 2004. "LES partnership is made up of limited and general partners currently consisting of Urenco, Exelon, Duke Power, Entergy, and Westinghouse."
Claiborne Enrichment Center, Homer, Claiborne Parish, Louisiana	Centrifuge/ Commercial	Deferred. License application withdrawn in 1998.	1,500 MTSWU/a	Source: IAEA NFCIS 1999 & NRC FAQ Centrifuges 2004. Owned by Louisiana Energy Services, L.P. (LES)
Lawrence Livermore National Laboratory, Livermore, California	AVLIS[40]/ Laboratory	Deferred. Startup 1991; Shutdown 1999	1 MTSWU/a	Source: IAEA NFCIS 2001. Owned by U.S. Dept. of Energy (DOE). Operated by USEC Inc. See also: http://www.llnl.gov.

Portsmouth Centrifuge, Portsmouth (or Piketon), Ohio[41]	Centrifuge/ Pilot Plant	To begin operating in 2005.[42]	0 MTSWU/a (as given by IAEA)	Source: IAEA NFCIS 2003. Operated by USEC Inc. Also called American Centrifuge Demonstration Facility (see USEC Fact Sheet Piketon).
Location	**Process/ Scale**	**Dates**	**Nominal capacity**	**Comments**
Nuclear weapons states, not signatories of the NPT: India, Israel, Pakistan				
India[43]				
Rattehalli Rare Materials Plant (RMP) near Mysore, Karnataka.[44]	Centrifuge/ Pilot-scale	Startup 1990	Not given. <3 MTSWU/a estimated[45]	NTI India 2003b. "Operated by Indian Rare Earths Limited (IREL)…a subsidiary of the Department of Atomic Energy (DAE)"
Uranium Enrichment Plant, Trombay, Mumbai at Bhabha Atomic Research Center (BARC)[46]	Centrifuge/ Pilot-scale	Completed 1985	Not given	CEIP 2002, p. 203 & NTI India 2003a.
Trombay	Laser/ Laboratory	Startup early 1980s	Not given	CEIP 2002, p. 203.
Center for Advanced Technology (CAT), Indore	Laser/ Pilot scale	Startup 1993	Not given	CNS 1999 & CEIP 2002, p. 128.
Israel				
Dimona	Laser and gas centrifuge/ Laboratory & pilot scale	Not given	Not given	CEIP 2002, p. 213. "Experimental/pilot-scale (?) laser and centrifuge-enrichment programs; operating"
Pakistan				
Khan Research Laboratories (KRL),[47] Kahuta, Punjab	Centrifuge/ Commercial	Startup 1984	5 MTSWU/a[48]	Source: IAEA NFCIS 2003 & CEIP 2002, p. 217. Owned & operated by Pakistan Atomic Energy Commission (PAEC).
Golra[49]	Centrifuge/ Laboratory	Not given	Not given	Source: CEIP 2002, p. 217. "Ultracentrifuge plant reportedly to be used as testing facility; operational status unknown."
Sihala	Centrifuge/ Laboratory	Not given	Not given	Source: CEIP 2002, p. 217. "Experimental-scale ultracentrifuge facility; operating."
Wah/Gadwal[50], near Wah	Not given	Under construction in late 1990s?	Not given	Source: CEIP 2002, p. 217 & Globalsecurity Pakistan 2004.

Location	Process/ Scale	Dates	Nominal capacity	Comments
States of concern to U.S.: Iran, Iraq, and North Korea				
Iran[51]				
Fuel Enrichment Facility (FEP) at Natanz Enrichment Plant	Centrifuge/ Commercial[52]	To startup early 2005.	250 MTSWU/a[53]	Source: NTI Iran 2003a & ISIS Iran 2003a. IAEA Director General visited the Natanz site on Feb. 21, 2003 – the first time that the IAEA had inspected both plants. Neither plant was enriching uranium at that time.[54]
Pilot Fuel Enrichment Plant (PFEP), Natanz Enrichment Plant	Centrifuge/ Pilot Plant	Startup August 2003[55]	Not given	Source: NTI Iran 2003b. "Will hold 1,000 centrifuges." "Subordinate to AEOI [Atomic Energy Organization of Iran]."
Kalaye Electric Company, Tehran	unknown	Not given	Not given	Source: NTI Iran 2003c & IAEA Iran 2004. This is a possible enrichment site.
Sharif University of Technology, Tehran	Centrifuge?	Not given	Not given	Source: CEIP 2002, p.268. "Alleged uranium centrifuge research program."
Lashkar-Abad, near Hashtgerd	Lasers or Centrifuge?	Not given	Not given	Source: NTI Iran 2003d. Suspected enrichment site. Part of the Research and Development Division of AEOI.
Ramandeh, near Hashtgerd	Centrifuge?	Not given	Not given	Source: NTI Iran 2003d. Suspected enrichment site. Part of the Karaj Agricultural and Medical Centre of AEOI.
Iraq[56]				
Al Tuwaitha	EMIS/[57] Prototype-scale	Not given	0 MTSWU/a	Source: CEIP 2002, p. 289. "[O]perational until damaged by Coalition air attack (1991)."
Al Tuwaitha	Centrifuge/ Prototype-scale	Not given	0 MTSWU/a	Source: CEIP 2002, p. 289. "[O]perations relocated to Rashdiya in 1987."
Rashdiya	Centrifuge/ Prototype-scale		0 MTSWU/a	Source: CEIP 2002, p. 289. "[O]perations terminated at the outbreak of the 1991 Gulf War."
Al Tuwaitha	Chemical exchange isotope separation method/ Laboratory	Not given	0 MTSWU/a	Source: CEIP 2002, p. 289. "[O]perational until damaged by Coalition air attack (1991)."

Al Tarmiya	EMIS/ Commercial	Not given	0 MTSWU/a	Source: CEIP 2002, p. 289. "[P]artially operational until damaged by Coalition air attack (1991); EMIS-related installations and equipment subsequently destroyed by IAEA.
Ash Sharqat	EMIS/ Commercial	Not given	0 MTSWU/a	Source: CEIP 2002, p. 289. "[U]nder construction until damaged by Coalition air attack (1991); EMIS-related installations and equipment subsequently destroyed by IAEA."
North Korea[58]				
Ch'ŏnma-san Uranium Milling Facility and Suspected Uranium Enrichment Facility	Not given	Not given	Not given	Source: NTI North Korea 2003. See also NTI North Korea 2004.
Hagap Underground Suspected Nuclear Facility[59]	Not given	Not given	Not given	Source: NTI North Korea 2003.
Laser Research Institute[60]	Not given	Not given	Not given	Source: NTI North Korea 2003.
T'aech'ŏn Underground Suspected Nuclear Facility	Not given	Not given	Not given	Source: NTI North Korea 2003.
Yŏngjŏ-ri Suspected Uranium Enrichment Facility[61]	Not given	Not given	Not given	Source: NTI North Korea 2003.
Location	**Process/ Scale**	**Dates/ Status**	**Nominal capacity**	**Comments**
Additional states - Commercial or research programs: Argentina, Australia, Brazil, Germany, Japan, Netherlands, South Africa, South Korea				
Argentina[62,63]				
Pilcaniyeu, Rio Negro (province)[64]	Gaseous diffusion/ Pilot plant	Startup before 1983.[65] Standby 1990.	20 MTSWU/a	Source: IAEA NFCIS 2003. Operated by Comision Nacional de Energia Atomica (CNEA) Web site at www.cnea.gov.ar .[66]
Pilcaniyeu (Phase 2)[67]	Gaseous diffusion/ Commercial	Under construction[68]	100 MTSWU/a	Source: Handbook 2004, page 215.[69]

Australia				
Silex, Lucas Heights Science & Technology Complex, New South Wales.[70]	Laser/[71] Laboratory	Startup 1992	0 MTSWU/a (as given by IAEA)	Source: IAEA NFCIS 2000. Owned & operated by Silex Systems Ltd.[72]
Brazil[73]				
BRN Enrichment, Aramar Experimental Center, Ipero, Sao Paolo (state)[74]	Centrifuge/ Laboratory	Startup 1992	5 MTSWU/a	Source: IAEA NFCIS 2003 and GlobalSecurity Brazil Ipero 2004. Owned by Ministry of Defense, operated by Navy.[75]
BRF Enrichment, Aramar Demonstration Center, Ipero, Sao Paolo (state)[76]	Centrifuge/ Pilot plant	Startup 1998[77]	4 MTSWU/a	Source: IAEA NFCIS 2003. Owned by Ministry of Defense, operated by Navy.[78]
Resende Enrichment, Engenheiro Passos, Rio de Janeiro (state)[79]	Centrifuge[80]/ Commercial	Under construction. 2004 startup planned (not started as of September 2004)	120 MTSWU/a[81]	Source: IAEA NFCIS 2003. Owner & operator: INB[82] In the past year, Brazil has blocked IAEA inspectors from certain parts of this plant, on grounds that proprietary information would be revealed. News reports claim that a compromise has been reached. The inspectors are due in Brazil on October 15, 2004.[83]
IPEN (Institute of Energy and Nuclear Research), Sao Paulo University.[84]	Centrifuge/ Pilot Scale	Startup 1982[85]	Not given	Redick 1995 & CEIP 2002. "A Navy-led program" (Redick 1995)
Sao Jose dos Campos, Aerospace Technical Center, near Sao Paulo	Laser (AVLIS)/ Laboratory	Startup 1981[86]	0 MTSWU/a (as given by the IAEA)	Source: IAEA NFCIS 2003. The Air Force operates this facility. (Krasno 1994).
Pilot Uranium Enrichment Plant, Belo Horizonte, Minas Gerais (MG)	Jet Nozzle/ Pilot plant	Startup 1979 Shutdown 1989 Decommis-sioning	0 MTSWU/a (as given by IAEA)	Source: IAEA NFCIS 2003. Owner: Comissao Nacional de Energia Atomica – Brazil. Operator: Centro Desenvolvimento de Technologie Nuclear. See also http://www.cdtn.br.
Sorocaba[87]	Centrifuge	proposed	Not given	Source: Handbook 2004, p. 215. Operator: IPEN.[88]
Resende Pilot Plant, Engenheiro Passos, Rio de Janeiro state	Jet Nozzle/ Pilot	Cancelled[89]	500 MTSWU/a[90]	Source: IAEA NFCIS 2003. Ownership: 75 %, Industrias Nucleares Do Brasil S.A. ,15 %, Interatom, 10 %, Steag. Operator: Nuclebras Anriquecimento Isotopico S.A. Krasno (1995) refers to this as an Army facility.

Germany[91]				
Urenco Deutschland, Gronau, North Rhine Westphalia	Centrifuge/ Commercial	Startup 1985	1800 MTSWU/a	IAEA NFCIS 2003. Owned by URENCO Enrichment Co Ltd; operated by URENCO Deutschland.[92] See also: http://www.urenco.com/unl/unl.htm.
Enrichment Technology Company, Juelich, North Rhine Westphalia	Centrifuge/ Laboratory	Startup 1964	0 MTSWU/a	Source: IAEA NFCIS 2003. Operated by: Enrichment Technology Company Ltd, which is part of Urenco.[93]
Karlsruhe Enrichment, Karlsruhe, Baden-Wuerttemberg	Jet Nozzle / Pilot Plant	Decommis-sioned	50 MTSWU/a	Source: IAEA NFCIS 2003. Owned & operated by Forschungszentrum Karlsruhe GmbH (FZK)
Japan[94]				
JNFL Rokkasho Enrichment Plant at Rokkasho / Kamikita-gun, Aomori prefecture	Centrifuge/ Commercial	Startup 1992	1050 MTSWU/a	IAEA NFCIS 2003. Owned & operated by Japan Nuclear Fuel Ltd (JNFL).[95]
JNC Ningyo-Toge Enrichment Demo. Plant (DOP)	Centrifuge/ Pilot Plant	Startup 1989. Shutdown 2004. Being dismantled[96]	200 MTSWU/a	Source: IAEA NFCIS 2003 & JNC Ningyo 2004. Owned & operated by Japan Nuclear Fuel Cycle Development Institute (JNC).
Ningyo-Toge Uranium Pilot Plant	Centrifuge/ Pilot Plant	Start up 1979; Shutdown 2004. Being dismantled.[97]	75 MTSWU/a	Source: IAEA NFCIS 2003. Owned & operated by Japan Nuclear Fuel Cycle Development Institute (JNC).
Asahi U Enrichment Laboratory, Hyuga, Miyazaki prefecture	Chemical Exchange/ Pilot Plant	Startup 1986; Shutdown 1991	2 MTSWU/a	Source: IAEA NFCIS 2003. Owned & operated by ASAHI Chemical Industry Co.
JNC Tokai (Enrichment Tests), Tokai-mura, Naka-gun, Ibaraki prefecture	Laser (MLIS)/ Laboratory	Startup 1991; Shutdown, 2003	0 MTSWU/a (as given by IAEA)	Source: IAEA NFCIS 2003. Owned & operated by Japan Nuclear Fuel Cycle Development Institute (JNC).[98]
Tokai Test Facility, Tokai-mura, Naka-gun, Ibaraki prefecture	Laser (AVLIS)/ Laboratory	Startup 1987; Shutdown 2005 (planned) Decommis-sioning.	0 MTSWU/a (as given by IAEA)	Source: IAEA NFCIS 2003. Owned & operated by Laser Atomic Separation Engineering Research Association of Japan.

Netherlands[99]				
Urenco Nederland Almelo, Overyssel Province	Centrifuge/ Commercial	Startup 1973	2,200 MTSWU/a	IAEA NFCIS 2003. Owned by URENCO Enrichment Co Ltd; operated by URENCO Nederland.[100]
South Africa				
Valindaba (Laser), Valindaba, North West.	Laser (MLIS)/ Pilot Plant	Deferred. Startup 1995; Shutdown 1998	30 MTSWU/a	Source: IAEA NFCIS 2003. Owned & operated by Atomic Energy Corporation Of South Africa Ltd (AEC).
Valindaba Y - Plant, Valindaba, North West.[101]	Jet Nozzle/ Pilot Plant	Startup 1978; Shutdown 1990. Decommis-sioning.	10 MTSWU/a	Source: IAEA NFCIS 2003. Owned & operated by Atomic Energy Corporation of South Africa Ltd (AEC). Estimated to have produced 550 kilograms of HEU for weapons (GlobalSecurity South Africa 2002).
Valindaba Z - Plant, Valindaba, North West.	HELICON/ Commercial	Startup 1986; Shutdown 1996. Decommis-sioning.	300 MTSWU/a	Source: IAEA NFCIS 2003. Owned & operated by Atomic Energy Corporation Of South Africa Ltd (AEC). IAEA NFCIS gives this Web site http://www.necsa.co.za, which does not mention Valindaba.
South Korea				
Korea Atomic Energy Research Institute (KAERI)[102]	Laser (AVLIS)/ Laboratory	Experiments performed in early 2000[103]	Not given	Gorwitz 2004; Reuters, September 2, 2004.

Table 2 highlights the fact that the knowledge and the ability to enrich uranium for either nuclear power or nuclear weapons are quite widespread. In many ways the horse has already gotten out of the barn when it comes to uranium enrichment techniques. This is a particularly serious concern in relation to ideas about expanding the future use of nuclear power around the world. With an expanded trade in the specialized materials required to build and operate gas centrifuge and other enrichment plants, illicit sales and diversion of supposedly "peaceful" materials will become harder to identify. As an example, in order to fuel one thousand 1,000 megawatt nuclear plants (a common reference case in many nuclear growth scenarios), a global uranium enrichment capacity of roughly 100,000 to 120,000 MTSWU would be required. If just 1% of that capacity was instead used to manufacture highly enriched uranium, then there would be enough HEU produced every year to make between 175 and 310 nuclear weapons. While focusing on countries that are currently making headway in efforts that could support a nuclear weapons program is important, it is also important to keep in mind how widespread the technology of uranium enrichment has become and how much greater the dangers would become if it is allowed to expand anywhere in the world (recall the information in Table 1) as part of an effort to expand the use of nuclear power.

Table 2 endnotes:

[1] Commercial scale refers to size. A commercial facility and a military facility differ primarily only in how they are run, not in how they are built. Many plants operated in the nuclear weapons states listed as commercial have produced HEU for nuclear weapons in the past.

[2] The secondary sources from which the Chinese data was compiled have a great deal of conflicting information, which makes it hard to determine how many plants have been built or are planned.

[3] As of December 31, 2003, IAEA listed one site in China under its Safeguards. It was: "Shaanxi" in "Han Zhang," (IAEA Annual Report 2003, Table A24).

[4] Nuclear Fuel, May 27, 2002. Startup date is not given, but as of May 2002, "current throughput…is about 30 tons SWU/yr."

[5] NTI China 2003.

[6] "Earlier reports said this plant might be located in Chengdu." (CEIP 2002, p. 162, note 7**).**

[7] There are two plants at this site producing LEU and under IAEA safeguards (NTI China 2003).

[8] NTI China 2003.

[9] CRISLA stands for Chemical reaction by isotope selective laser activation (IAEA 1995).

[10] "Possible enrichment facility for weapons-grade uranium." (NTI China 2003).

[11] Tricastin and Pierrelatte are separate places, adjacent to each other. Sometimes the names "get swapped around." (Davis e-mail).

[12] Davis (English) refers to this place as Tricastin/Pierrelatte.

[13] To be replaced by the Georges Besse II centrifuge plant, in stages beginning in 2007. (Davis (English)).

[14] "France formed Eurodif in 1997 in partnership with Belgium, Iran, Italy and Spain." (Albright, Berkhout & Walker 1997, p.123). Eurodif is a subsidiary of Cogema. See more at www.cogema.com.

[15] Davis (English) refers to this location as Tricastin/Pierrelatte.

[16] "Séparation Isotopique par Laser de la Vapeur Atomique d'uranium" Known as AVLIS in English.

[17] CEA and the French Government agreed to shutdown by end of 2003. "France has abandoned development of Silva." (Davis (English)).

[18] Known in France as SILVA or Séparation Isotopique par Laser de la Vapeur Atomique d'uranium.

[19] We could find no more information about the P (Laser).

[20] CEA and the French Government agreed to shutdown by end of 2003. "France has abandoned development of Silva." (Davis (English)).

[21] "The Soviet Union stopped production of highly enriched uranium for weapons by 1989." (NTI Russia 2003).

[22] "As of May 2001…involved in down-blending HEU to low enriched uranium (LEU) under the US-Russian HEU Deal." (NTI Russia 2003).

[23] Also known as Ural Electrochemistry Kombinat (Albright, Berkhout & Walker 1997, p. 96) or UEK), or Sverdlovsk-44 or Urals Electrochemical Integrated Plant, at Novouralsk (CEIP 2002, p. 132).

[24] All the Russian plants started as gaseous diffusion plants but were upgraded with gas centrifuges beginning in 1960's (Albright, Berkhout & Walker 1997, p. 97).

[25] "As of May 2001…involved in down-blending HEU to low enriched uranium (LEU) under the US-Russian HEU Deal." (NTI Russia 2003).

[26] Also known as Siberian Chemical Kombinat, or Tomsk-7 (Albright, Berkhout & Walker 1997, p. 97).

[27] Feed material is reprocessed uranium. (IAEA NFCIS 2003).

[28] "As of May 2001…involved in down-blending HEU to low enriched uranium (LEU) under the US-Russian HEU Deal." (NTI Russia 2003).

[29] Also known as Electrochemistry Kombinat, Krasnoyarsk-45 or Zelenogorsk (Albright, Berkhout & Walker 1997, p. 97 and CEIP 2002, p. 128).

[30] Also known as Electrolyzing Chemical Kombinat (Albright, Berkhout & Walker 1997, p. 97).

[31] As of December 31, 2003, IAEA listed one site in the UK under its Safeguards. It is: "URENCO E22, E23 & A3 plant" in Capenhurst (IAEA Annual Report 2003, Table A24).

[32] "In late 1997, the new gas centrifuge enrichment plant E23 went into operation." (IAEA NFCIS 2003); E21 plant shutdown in 1991 and has been decommissioned (WNA Capenhurst).

[33] "The capacity of the facility has been increased to 2300 MTSWU/a from its previous level 1300 MTSWU/a." (IAEA NFCIS 2003, Urenco Capenhurst record, News/Events entry for 12-31-03). "In late 1997, the new gas centrifuge enrichment plant E23 went into operation at the Urenco Capenhurst site in the United Kingdom." (IAEA NFCIS 2003, Urenco Capenhurst record, News/Events entry for 3-22-99).

[34] Original plant operated by BNFL (WNA Capenhurst).

[35] USEC says this is currently "the only operating enrichment facility in United States." (USEC Paducah).
[36] Updated in the 1970s (Albright, Berkhout & Walker 1997, p. 471).
[37] Updated in the 1970s (Albright, Berkhout & Walker 1997, p. 471).
[38] USEC ceased enrichment activities in May 2001 and is on "cold-standby." (USEC Portsmouth GD).
[39] The application to build and operate the plant was submitted to the NRC on August 23, 2004. (USEC News release 2004).
[40] AVLIS stands for "atomic vapor laser isotope separation" process.
[41] USEC calls this pilot plant the American Centrifuge Demonstration Plant (Phase 1 per NRC) (NRC calls phase 2 "Lead Cascade" (USEC Fact Sheet Piketon & NRC Portsmouth).
[42] USEC Fact Sheet Piketon. The NRC issued Material License SNM-7003 to USEC Inc. for the lead cascade facility on February 24, 2004. (NRC Portsmouth).
[43] CEIP 2002 lists only pilot scale or research sites.
[44] "[O]perates several hundred domestically produced sub-critical centrifuge rotor assemblies." "The output…is estimated at fewer tha[n] three separative work units per machine per year." (NTI India 2003b).
[45] **"**The plant operates several hundred domestically produced sub-critical centrifuge rotor assemblies.**"** and the **"**output of the Rattehalli Plant is estimated at fewer tha[n] three separative work units per machine per year**"** (NTI India 2003b).
"output of the Rattehalli Plant is estimated at fewer that three separative work units per machine per year**"**
[46] "As of the early 1990s…[it] was operating 100 gas centrifuges." (NTI India 2003).
[47] CEIP 2002, p. 217. Also known as A.Q. Khan Research Laboratories (Nuclear Weapon Archive 2001).
[48] "The capacity will be expanded to approx. 15 MSWU[sic] (NEI)" (IAEA NFCIS 2003, 8/1/03 entry under News/events in the Kahuta report).
[49] "It is expected to be even larger than Kahuta" (Nuclear Weapon Archive 2001).
[50] "[D]esignated the Gadwal Uranium Enrichment Plant by the US government." "This facility may [or may not] be the otherwise un-attested 'Uranium Conversion Facility, Islamabad.'" (GlobalSecurity Pakistan 2004).
[51] As of December 31, 2003, IAEA listed one site in Iran under its Safeguards. It is: "PFEP" in Natanz (IAEA Annual Report 2003, Table A24).
[52] To "contain 50,000 centrifuges when it became fully operational." (NTI Iran 2003a).
[53] "If each centrifuge has an enrichment capacity of up to 5 SWU per year, the total capacity of this facility when finished is estimated to be up to 250,000 SWU per year." (ISIS Iran 2003a).
[54] GlobalSecurity Iran 2004.
[55] GlobalSecurity Iran 2004.
[56] The Iraqi nuclear program was brought to a halt by the 1991 Gulf War and subsequent U.N. inspections. As of April 2003, when the U.S. and British lead invasion of Iraq toppled the government all Iraqi facilities were shutdown. See a brief description of Iraqi enrichment facilities in NTI Iraq 2003.
[57] Electromagnetic isotope separation method.
[58] We list possible sites. This is very uncertain information.
[59] According to NTI, U.S. government believes that Hagap, Laser Research Institute (part of the Academy of Sciences), and Yŏngjŏ-ri are the most likely sites.
[60] According to NTI, U.S. government believes that Hagap, Laser Research Institute (part of the Academy of Sciences), and Yŏngjŏ-ri are the most likely sites.
[61] According to NTI, U.S. government believes that Hagap, Laser Research Institute (part of the Academy of Sciences), and Yŏngjŏ-ri are the most likely sites.
[62] These facilities are frequently referred to as a one. The Pilcaniyeu facility was placed under IAEA safeguards in 2000. It is the first gaseous diffusion uranium enrichment plant to be safeguarded by the IAEA (GlobalSecurity Argentina 2004).
[63] As of December 31, 2003, IAEA listed one site in Argentina under its Safeguards. It is: "Pilcaniyeu enrichment plant" in Pilcaniyeu (IAEA Annual Report 2003, Table A24).
[64] "Phase 1" (Handbook 2004, p. 215).
[65] Albright, Berkhout & Walker 1997, p. 370.
[66] Handbook 2004 lists operator as NASA (Nucleoeléctrica Argentina SA). NASA was formed in 1994 (CNEA 2000).
[67] Is this the "renovated pilot…plant" opened in December 1993, cited by Albright, Berkhout & Walker 1997, p. 371?
[68] Planning or construction possibly started in 1997. (GlobalSecurity Argentina 2004).
[69] Handbook 2004 lists operator as NASA (Nucleoeléctrica Argentina SA). It may instead be operated by Comision Nacional de Energia Atomica (CNEA).
[70] http://www.silex.com.au/: "Silex has traditionally viewed the US market as the most likely home for SILEX Uranium Enrichment technology. … The Uranium application of SILEX is currently in stage 2 of a 3 stage development program, involving the verification of process efficiency and economics in a significant scale engineering prototype facility. Stage 2 is

expected to be complete in late 2004 or early 2005. Stage 3 involves the construction and operation of a Pilot Plant Facility, probably in the US."

[71] Called SILEX or **S**eparation of **I**sotopes by **L**aser **Ex**citation.

[72] See also http://www.silex.com.au.

[73] As of December 31, 2003, IAEA listed three sites in Brazil under its Safeguards. They are: "Enrichment Laboratory" in Ipero, "Uranium enrichment pilot plant" in Sao Paulo, and the "Laser spectroscopy lab" in San Jose dos Campos (IAEA Annual Report 2003, Table A24).

[74] Aramar Research Center is the collective and/or later name for the Demonstration and Experimental Centers. (e.g. CDI 2004).

[75] See also http://www.ctmsp.mar.mil.br/.

[76] Aramar Research Center is the collective and/or later name for the Demonstration and Experimental Centers. One of the Aramar plants or the combined plants are also referred to as the Isotopic Enrichment Facility or LEI (Sublette Brazil).

[77] After the success in enriching uranium at IPEN in Sao Paulo, "the navy initiated development of a pilot-scale gas centrifuge facility (Aramar) in Ipero" (Redick 1995).

[78] See also http://www.ctmsp.mar.mil.br/.

[79] Also known as Resende Nuclear Fuel Factory (FCN) or Fábrica de Combustível Nuclear FCN – Enriquecimento. (INB Resende).

[80] "[U]ltra-centrifuge" (INB Resende).

[81] Ultimately to be "200 t SWU/a" (GlobalSecurity Brazil Resende 2004).

[82] Industrias Nucleares Do Brasil, with Web site at http://www.inb.gov.br.

[83] For example, see Washington Post, April 4, 2004 and ABC News, October 6, 2004.

[84] "Enriched a small amount of uranium beginning in late 1986, an accomplishment that was publicly announced in September 1987." (Redick 1995).

[85] Sublette Brazil.

[86] "Not operational" (CEIP 2002, p.355).

[87] Sorocaba is a city near Sao Paulo. We are not sure what facility this is. We found listed only in the Handbook (2004).

[88] Instituto de Pesquisas Energéticas e Nucleares (IPEN/CNEN-SP) or Institute for Energy and Nuclear Research. Web site for IPEN: http://www.ipen.br/.

[89] Government stopped work on the jet nozzle project (IAEA NFCIS 2003, narrative dated 7/1/98 under Resende Enrichment)

[90] IAEA gives this large number.

[91] As of December 31, 2003, IAEA listed one site in Germany under its Safeguards. It was: "UTA" in Gronau (IAEA Annual Report 2003, Table A24).

[92] See also: http://www.urenco.com/unl/unl.htm.

[93] See also http://www.urenco.com/index.php?id=172&cid=209&pagename=Juelich+-+Gronau.

[94] As of December 31, 2003, IAEA listed two sites in Japan under its Safeguards. They are: "Uranium Enrichment Plant" in Tomata-gun, Okayama-ken and "Rokkasho Enrichment Plant" in Kamikita-gun, Aomori-ken (IAEA Annual Report 2003, Table A24).

[95] See also http://www.jnfl.co.jp/english/our_business/uranium-enrichment/.

[96] JNC Ningyo-toge 2004.

[97] JNC Ningyo-toge 2004.

[98] See also http://www.jnc.go.jp/jncweb/index.htm.

[99] As of December 31, 2003, IAEA listed one site in the Netherlands under its Safeguards. It is: "URENCO" in Almelo (IAEA Annual Report 2003, Table A24).

[100] See also: http://www.urenco.com/unl/unl.htm.

[101] Also known as Pelindaba East. This plant is adjacent to the Pelindaba Nuclear Research Center. (GlobalSecurity South Africa 2002).

[102] Gorwitz 2004.

[103] Reuters, September 2, 2004. According to the Reuters report, the South Korean Government statement said that "all facilities and the uranium were destroyed immediately after the experiments."

Adapted from http://www.ieer.org/fctsheet/uranium.html.

Appendix 1: Uranium: Its Uses and Hazards

Some of the terms used in this fact sheet are defined in IEER's on-line glossary at http://www.ieer.org/clssroom/glossary.html

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First discovered in the 18th century, uranium is an element found everywhere on Earth, but mainly in trace quantities. In 1938, German physicists Otto Hahn and Fritz Strassmann showed that uranium could be split into parts to yield lighter elements, neutrons, and energy. Uranium is the principal fuel for nuclear reactors and the main raw material for nuclear weapons.

Natural uranium consists of three isotopes: uranium-238, uranium-235, and uranium-234. All uranium isotopes are radioactive. The nuclei of radioactive elements are unstable, meaning they are transformed into other elements, typically by emitting particles (and sometimes by absorbing particles). This process, known as radioactive decay, generally results in the emission of alpha or beta particles (helium nuclei and electrons respectively) from the nucleus. It is often also accompanied by emission of gamma radiation, which is electromagnetic radiation, like X-rays. These three kinds of radiation have very different properties in some respects but are all ionizing radiation--each is energetic enough to break chemical bonds, thereby possessing the ability to damage or destroy living cells.

Summary of Uranium Isotopes				
Isotope	**Percent in natural uranium**	**No. of Protons**	**No. of Neutrons**	**Half-Life (in years)**
Uranium-238	99.284	92	146	4.46 billion
Uranium-235	0.711	92	143	704 million
Uranium-234	0.0055	92	142	245,000

Uranium-238, the most prevalent isotope in uranium ore, has a half-life of about 4.5 billion years; that is, half the atoms in any sample will decay in that amount of time. Uranium-238 decays by alpha emission into thorium-234, which itself decays by beta emission to protactinium-234, which decays by beta emission to uranium-234, and so on. The various decay products, (sometimes referred to as "progeny" or "daughters") form a series starting at uranium-238. After several more alpha and beta decays, the series ends with the stable isotope lead-206.

URANIUM DECAY CHAIN -- Main Branch Read from left to right. Arrows indicate decay.		
Uranium-238 ==> (half-life: 4.46 billion years) alpha decay	Thorium-234 ==> (half-life: 24.1 days) beta decay	Protactinium-234m ==> (half-life: 1.17 minutes) beta decay
Uranium-234 ==> (half-life: 245,000 years) alpha decay	Thorium-230 ==> (half-life: 75,400 years) alpha decay	Radium-226 ==> (half-life: 1,600 years) alpha decay
Radon-222 ==> (half-life: 3.82 days) alpha decay	Polonium-218 ==> (half-life: 3.11 minutes) alpha decay	Lead-214 ==> (half-life: 26.8 minutes) beta decay
Bismuth-214 ==> (half-life: 19.9 minutes) beta decay	Polonium-214 ==> (half-life: 163 microseconds) alpha decay	Lead-210 ==> (half-life: 22.3 years) beta decay
Bismuth-210 ==> (half-life: 5.01 days) beta decay	Polonium-210 ==> (half-life: 138 days) alpha decay	Lead-206 (stable)

Uranium-238 emits alpha particles which are less penetrating than other forms of radiation, and weak gamma rays. As long as it remains outside the body, uranium poses little health hazard (mainly from the gamma-rays). If inhaled or ingested, however, its radioactivity poses increased risks of lung cancer and bone cancer. Uranium is also chemically toxic at high concentrations and can cause damage to internal organs, notably the kidneys. Animal studies suggest that uranium may affect reproduction, the developing fetus,[(1)] and increase the risk of leukemia and soft tissue cancers.[(2)]

The property of uranium important for nuclear weapons and nuclear power is its ability to fission, or split into two lighter fragments when bombarded with neutrons releasing energy in the process. Of the naturally-occurring uranium isotopes, only uranium-235 can sustain a chain reaction – a reaction in which each fission produces enough neutrons to trigger another, so that the fission process is maintained without any external source of neutrons.[(3)] In contrast, uranium-238 cannot sustain a chain reaction, but it can be converted to plutonium-239, which can sustain a chain reaction.[(4)] Plutonium-239, virtually non-existent in nature, was used in the first atomic bomb tested July 16, 1945, and in the one that was dropped on Nagasaki on August 9, 1945.

The Mining and Milling Process

Traditionally, uranium has been extracted from open-pits and underground mines.

In the past decade, alternative techniques such as in-situ leach mining, in which solutions are injected into underground deposits to dissolve uranium, have become more widely used. Most mines in the U.S. have shut down and imports account for about three-fourths of the roughly 16 metric tons of refined uranium used domestically each year – Canada being the largest single supplier.(5)

The milling (refining) process extracts uranium oxide (U_3O_8) from ore to form yellowcake, a yellow or brown powder that contains about 90 percent uranium oxide.(6) Conventional mining techniques generate a substantial quantity of mill tailings waste during the milling phase because the usable portion is generally less than one percent of the ore. (In-situ leach mining leaves the unusable portion in the ground, and therefore does not generate this type of waste). The total volume of mill tailings generated in the U.S. is over 95 percent of the volume of all radioactive waste from all stages of the nuclear weapons and power production.(7) While the hazard per gram of mill tailings is low relative to most other radioactive wastes, the large volume and lack of regulations until 1980 have resulted in widespread environmental contamination. Moreover, the half-lives of the principal radioactive components of mill tailings, thorium-230 and radium-226 are long, being about 75,000 years and 1,600 years respectively.

The most serious health hazard associated with uranium mining is lung cancer due to inhaling uranium decay products. Uranium mill tailings contain radioactive materials, notably radium-226, and heavy metals (e.g., manganese and molybdenum) which can leach into groundwater. Near tailings piles, water samples have shown levels of some contaminants at hundreds of times the government's acceptable level for drinking water.(8)

Mining and milling operations have disproportionately affected indigenous populations around the globe. For example, nearly one third of all mill tailings from abandoned mill operations are on lands of the Navajo nation alone.(9) Many Native Americans have died of lung cancers linked to their work in uranium mines. Others continue to suffer the effects of land and water contamination due to seepage and spills from tailings piles.(10)

Conversion and Enrichment

Uranium is generally used in reactors in the form of uranium dioxide (UO_2) or uranium metal, while nuclear weapons use only the metallic form. Production of uranium dioxide or metal requires the chemical processing of yellowcake. Further, most civilian and many military reactors require uranium that has a higher proportion of uranium-235 than present in natural uranium. The process used to increase the amount of uranium-235 relative to uranium-238 is known as uranium enrichment.

U.S. civilian power plants typically use 3 to 5 percent uranium-235. Weapons use "highly enriched uranium" (HEU) with over 90 percent uranium-235. Some

research reactors and all U.S. naval reactors also use HEU.

To enrich uranium, it must first be put in the chemical form uranium hexafluoride (UF_6). After enrichment, UF_6 is chemically converted to uranium dioxide or metal. A major hazard in both the uranium conversion and uranium enrichment processes comes from the handling of uranium hexafluoride, which is chemically toxic as well as radioactive. Moreover, it reacts readily with moisture, releasing highly toxic hydrofluoric acid. Conversion and enrichment facilities have had a number of accidents involving uranium hexafluoride.[11]

The bulk of waste from the enrichment process is depleted uranium--so-called because much of the uranium-235 has been extracted from it. Depleted uranium has been used by the U.S. military to fabricate armor-piercing conventional weapons and tank armor plating. It was incorporated into these conventional weapons without informing armed forces personnel that depleted uranium is a radioactive material and without procedures for measuring doses to operating personnel or exposed civilians.

The enrichment process can also be reversed. Highly enriched uranium can be diluted, or "blended down" with depleted, natural, or very low-enriched uranium to produce 3 to 5 percent low-enriched reactor fuel. Uranium metal at various enrichments must be chemically processed so that it can be blended into a homogeneous material at one enrichment level. As a result, the health and environmental risks of blending are similar to those for uranium conversion and enrichment.

Regulations in the U.S.

In 1983 the federal government set standards for controlling pollution from active and abandoned mill tailings piles resulting from yellowcake production. The principal goals of federal regulations are to limit the seepage of radionuclides and heavy metals into groundwater and reduce emissions of radon-222 to the air. Mandatory standards for decommissioning nuclear facilities including uranium conversion and enrichment facilities are only now being developed by the U.S. Environmental Protection Agency and the U.S. Nuclear Regulatory Commission (NRC).

The Future

Uranium and associated decay products, thorium-230 and radium-226, will remain hazardous for thousands of years. Current U.S. regulations, however, cover a period of just 1,000 years for mill tailings and at most 500 years for "low-level" radioactive waste. This means that future generations--far beyond those promised protection by these regulations--will likely face significant risks from uranium mining, milling, and processing activities.

Appendix 1 References:

1. Agency for Toxic Substances and Disease Registry, Public Health Statement for Uranium, Atlanta, December 1999. Link on the Web at http://www.atsdr.cdc.gov/toxprofiles/tp150.html. For additional information on uranium health risks and plausible disposal strategies see Arjun Makhijani and Brice Smith, Costs and Risks of Management and Disposal of Depleted Uranium from the National Enrichment Facility Proposed to be Built in Lea County New Mexico by LES. Takoma Park, MD: Institute for Energy and Environmental Research, November 24, 2004. Version for Public Release Redacted February 1, 2005.

2. Filippova, L. G., A. P. Nifatov, and E. R. Lyubchanskii, Some of the long-term sequelae of giving rats enriched uranium (in Russian), Radiobiologiya, v. 18, n. 3, pp. 400-405. 1978. Translated in NTIS UB/D/120-03 (DOE-TR-4/9), National Technical Information Service, Springfield, Virginia.

3. Uranium-235 and plutonium-239 are called "fissile" isotopes--defined as materials that can be fissioned by low-energy (ideally zero energy) neutrons.

4. Uranium-238 is converted to plutonium-239 by bombarding it with neutrons: U-238 + neutron -->> U-239 followed by U-239 ==> Np-239 + beta particle (electron) followed by Np-239 ==> Pu-239 + beta particle (electron)

5. Energy Information Administration, Uranium Purchases Report 1992, DOE/EIA-0570(92), Washington, D.C., August 1993. The number of conventional mines operating in the U.S. has declined from a peak of hundreds to zero in 1993, seven "non-conventional" mining operations (e.g., in-situ leach) accounted for all domestic ore production for that year. (NUEXCO, NUEXCO Review: 1993 Annual, Denver, 1994).

6. Benedict, Manson, Thomas Pigford, and Hans Wolfgang Levi. Nuclear Chemical Engineering. 2nd ed. (New York: McGraw-Hill Book Company, 1981), p. 265. Note that pure U3O8 is black. Yellowcake gets its color from the presence of ammonium diuranate.

7. Based on the total volume of all radioactive waste (including spent fuel, high-level waste, transuranic waste, low-level waste and uranium mill tailings) from all sources (both commercial and military) produced in the U.S. since the 1940s, as compiled in Scott Saleska, et al. Nuclear Legacy: An Overview of the Places, Politics, and Problems of Radioactive Waste in the United States (Washington, DC: Public Citizen, 1989), Appendix C.

8. U.S. Environmental Protection Agency, Final Environmental Impact Statement for Standards for the Control of Byproduct Materials from Uranium Ore Processing, Washington, D.C., 1983, v. 1, pp. D-12, D-13.

9. Gilles, Cate, Marti Reed, and Jacques Seronde, Our Uranium Legacy, 1990 [available from Southwest Research and Information Center, Albuquerque, NM].

10. In 1979, a dam holding water in a mill tailings settling pond at the United Nuclear Fuels Corporation mill near Church Rock, New Mexico, gave way and released about 100 million gallons of contaminated water into the Puerco River which cuts through Navajo grazing lands.

11. One such accident at the Sequoyah Fuels conversion plant in Gore, Oklahoma, killed one worker, hospitalized 42 other workers, and sent approximately 100 residents to the hospital as well.

Nuclear Regulatory Commission's Uranium Enrichment Fact Sheet, June 2004.
On the Web at http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/enrichment.pdf.

Appendix 2: Uranium Enrichment and the U.S. Nuclear Regulatory Commission

Background

The fuel of a nuclear power plant is uranium, but only a certain type of uranium atom can be easily split to produce energy. This type of uranium atom – called uranium-235 (U_{235}) – comprises less than one percent by weight of the uranium as it is mined or milled. To make fuel for reactors, the natural uranium is enriched to increase the concentration of U_{235} to three to five percent.

The uranium fuel cycle begins by mining and milling uranium ore to produce "yellow cake," which is then converted into uranium hexafluoride (UF_6). The UF_6 is then enriched before being made into nuclear fuel. Throughout the global nuclear industry, uranium is enriched by one of two methods: gaseous diffusion and gas centrifuge.

Gaseous Diffusion

Gaseous diffusion is based on the separation effect arising from molecular effusion (i.e., the flow of gas through small holes). In a vessel containing a mixture of two gases, molecules of the gas with lower molecular weight (U_{235} as opposed to the heavier and more plentiful U_{238}) travel faster and strike the walls of the vessel more frequently, relative to their concentration, than do molecules with higher molecular weight. Assuming the walls of the vessel are semi-permeable, more of the lighter molecules flow through the wall than the heavier molecules. The gas that escapes the vessel is enriched in the lighter isotope. Currently, the United States uses the gaseous diffusion process to enrich uranium. There are two gaseous diffusion plants in the United States, at Piketon, Ohio, and Paducah, Kentucky. Both are operated by the United States Enrichment Corporation (USEC), which was created as a government corporation under the Energy Act of 1992 and privatized by legislation in 1996. Although the Ohio plant no longer enriches uranium commercially, it is where USEC intends to locate its proposed Lead Cascade facility to test the gas centrifuge process for the U.S. market (see below).

Gas Centrifuge

The gas centrifuge process has been widely used in Europe for about 30 years to enrich uranium for the commercial nuclear power market. The process uses a large number of rotating cylinders interconnected to form cascades. The UF_6 gas is placed in the cylinder and rotated at a high speed. The rotation creates a strong centrifugal force that draws the heavier gas molecules (containing the U_{238}) toward the outside of the cylinder, while the lighter gas molecules (containing the U_{235}) tend to collect closer to the center. The stream that is slightly enriched in U_{235} is withdrawn and fed into the next higher stage, while the slightly depleted stream is recycled back into the next lower stage. Significantly more U_{235} enrichment can be obtained from a single gas centrifuge stage than from a single gaseous diffusion stage. Two companies, USEC and Louisiana Energy Services (LES), have notified the NRC that they are considering constructing gas centrifuge facilities. In February 2004, the NRC issued a license for USEC to construct and operate a demonstration and test facility known as the Lead Cascade, to be located at Piketon, Ohio. USEC plans to submit an application in August 2004 for a commercial facility

to be located in Piketon. LES submitted its application and environmental report in December 2003 for a commercial facility to be located in Eunice, New Mexico. Under a Commission order, the NRC staff is to complete its review of the LES application by June 2006.

NRC Responsibilities

The NRC licenses and inspects all commercial nuclear fuel facilities involved in the processing and fabrication of uranium ore into reactor fuel, including facilities that enrich uranium. The agency currently has two full-time resident inspectors at USEC's enrichment plant in Kentucky, and specialized inspections are conducted using personnel from NRC headquarters in Maryland and the regional offices. The NRC also reports to Congress on the status of USEC's gaseous diffusion plants whenever the agency renews the company's certificate of compliance. The current certificates will expire on December 31, 2008, unless USEC has submitted an acceptable renewal application before that date. The next report to Congress will be issued following the renewal decision at that time.

Under the Atomic Energy Act, as amended, any new uranium enrichment plant must be licensed by the NRC under Title 10 of the Code of Federal Regulations Parts 40 (source material) and 70 (special nuclear material). The NRC performs a safety and security review of the plant and an environmental review of the impact of plant construction, operation, and decommissioning on the local environment.

If the application is for a commercial production facility, the NRC will conduct a "scoping" meeting to get public input into the types of issues to be addressed in the environmental review. Following the scoping process, NRC will prepare a draft Environmental Impact Statement (EIS) to assess the proposed facility's potential impact on public health and safety and the environment, including land, air and water resources, and offer a formal opportunity for the public to comment on it. The EIS process is expected to take 18 to 22 months. If the application is for a test facility, such as USEC's Lead Cascade, then an EIS may not be required and the NRC may prepare an Environmental Assessment (EA). An EA is less detailed than an EIS and results in either a finding of no significant impact (FONSI) or a decision to conduct a full EIS. Preparation of an EA does not require a scoping process or a formal opportunity for the public to comment on a draft version. The EA process is expected to take about 12 months.

Appendix 3: Depleted Uranium in the United States

Adapted from the website of Institute for Energy and Environmental Research (www.ieer.org)

DUF_6. Depleted Uranium Hexafluoride, is the by-product of uranium enrichment, and is the chemical form of most depleted uranium. Depleted uranium (DU) is also stored in other chemical forms, such as metal and oxide. (See Table 3-1.)

Table 3-1
Depleted Uranium Stocks in the U.S., by Chemical Form, as of 1996*

Form	Quantity (metric tons)	Percent of Total DU
UF_6	557,000**	95.21
Other		
UO_3	19,564	3.34
Metal	5,270	0.90
UF_4	2,982	0.51
Other Oxides	145	0.02
Miscellaneous and Scrap	35	0.01

* Source: DOE 1996, United States. Department of Energy. Office of Environmental Management. Office of Strategic Planning and Analysis. *Taking Stock: A Look at the Opportunities and Challenges Posed by Inventories from the Cold War Era*. Volume 1. A Report of the Materials in Inventory (MIN) Initiative. DOE/EM-0275. Washington, DC, January 1996. Fig. 2-20. Does not include classified inventories.
** Estimated stockpile as of 1999, stored at Paducah, Portsmouth and Oak Ridge totaled 739,000 metric tons (DOE 1999, United States. Department of Energy. Office of Nuclear Energy, Science and Technology. *Final Programmatic Environmental Impact Statement for Alternative Strategies for the Long-Term Management and Use of Depleted Uranium Hexafluoride*. Volume 1. Main Text. DOE/EIS-0269. Germantown, MD, April 1999. p. S-2).

How DUF_6 is Made

Natural uranium is composed of three isotopes: uranium-238 (99.284 percent); uranium-235 (0.711 percent); and, uranium-234 (0.005 percent), all of which are radioactive. The purpose of uranium enrichment is to concentrate uranium-235, the fissile isotope, in one stream. The other stream which is low in uranium-235, is called depleted uranium (DU), which typically contains only 0.2 to 0.3 percent uranium-235.

The enriched uranium is then further processed to varying degrees of enrichment. Uranium with between 3 and 5 percent uranium-235 (Low Enriched Uranium or LEU) is used as nuclear fuel for commercial nuclear power plants. An enrichment over 93.5

percent uranium-235 (Highly Enriched Uranium or HEU) can be used as material for nuclear weapons. In the U.S. is it also used in naval reactors. About 180 kilograms (kg) of depleted uranium result from the production of 1 kg of HEU with 93.5 percent uranium-235. Five to 10 kilograms of depleted uranium result from the production of 1 kg of LEU, depending on the degree of enrichment. Enrichment plants generally require uranium to be converted into the hexafluoride chemical form for processing reasons.

Storage of DUF_6 and Environmental, Health and Safety Hazards

Currently there are about 560,000 metric tons of DUF_6 stored primarily in 14-ton cylinders located near Portsmouth, Ohio; Oak Ridge, Tennessee; and Paducah, Kentucky. The long-term storage of DUF_6 presents environmental, health and safety hazards due to the chemical instability of UF_6. When UF_6 is exposed to moist air, it reacts with the water in the air to produce UO_2F_2 (uranyl fluoride) and HF (hydrogen fluoride) both of which are toxic. Storage cylinders must be regularly inspected for evidence of corrosion and leakage. Continuing to store depleted uranium in cylinders would require constant maintenance and monitoring of the stockpile because the estimated life-time of the cylinders is measured in decades, while the half-life of the main constituent of DU, uranium-238 is about 4.5 billion years.

Classification of Depleted Uranium

Currently, depleted uranium is still classified as a source material although its possible uses are few. The major uses of depleted uranium (i.e. to produce armor-piercing shells and armor plating for tanks) -- are likely to be phased out due to concerns about its radioactivity and heavy metal toxicity. Hence, DU is essentially a radioactive waste, though it has not been declared as such. The Department of Energy (DOE) has begun a process for considering how DU ought to be managed and how it should be disposed of if it is declared a waste.

In its consideration of a license application for a new uranium enrichment plant in Louisiana, the Nuclear Regulatory Commission (NRC), declared that DU from the plant would be considered "Class A" "low-level" radioactive waste. "Class A" is the category for the least dangerous "low-level" radioactive waste. The NRC made this declaration under the default provision for unclassified wastes in the Code of Federal Regulations 10 CFR 61.55. This classification is fundamentally flawed and potentially dangerous.

The NRC's own research demonstrates why this default classification is wrong. In a 1994 report, it determined that shallow-land burial, the usual means for disposing of Class A low-level radioactive waste, would be inappropriate for DU because it could result in unacceptably high doses in the future.[1]

A sound disposal program for managing DU as waste needs to be based on the

properties of depleted uranium, not a flawed and arbitrary classification system.

Properties of Depleted Uranium

Health and environmental effects of radioactive materials are affected by several factors: the specific activity of the radioactive material (the radioactivity per unit weight); the nature of the radiation being emitted during the radioactive decay (alpha or beta, and whether the decay is accompanied by gamma radiation); the energy per radioactive decay, the half-life; and the behavior of the specific radionuclide and its various chemical forms in the body. As illustrated in Tables 1 and 2, depleted uranium is the same as transuranic waste (TRU waste) in all essential respects that matter to health and the environment.[2] The difference is terminologically not substantive.

Table 3-2 illustrates that the specific activity (here, radioactivity per gram) of depleted uranium in any form is 2.7 to 4 times more than the minimum specific activity of transuranic waste.

Table 3-2:
Specific Activities of Various Chemical Forms of Depleted Uranium Compared to Transuranic Waste and Uranium Ore

Chemical form	Specific activity: (nanocuries[3] per gram)
Depleted uranium oxide (DU_3O_8)	340
Depleted uranium hexafluoride (DUF_6)*	270
Transuranic activity in TRU waste[2]	100
0.2 % uranium ore (including decay products)	4

* By comparison, the specific activity of uranium-238 is 340 nanocuries per gram.

Table 3-3 compares isotopes of uranium and selected transuranic elements. It is clear that in all cases, the predominant mode of decay is the same (alpha decay) and that the decay energies are about the same (ranging from 4.1 to 5.5 mega-electron volts). Thus, the amount of radiation dose per radioactive decay of DU is approximately the same as that of a radioactive decay of a transuranic radionuclide of TRU waste.

Table 3-3

Properties of Uranium Isotopes and Selected Long-Lived Transuranic Elements

Isotope	Main decay mode	Alpha particle energy, MeV	Half-life in years	Comments
Uranium Isotopes:				
uranium-238	alpha	4.1	4.46 billion	
uranium-235	alpha	4.7	704 million	
uranium-234	alpha	4.8	245,000	
Transuranics:				
neptunium-237	alpha	4.8	2.14 million	
plutonium-238	alpha	5.5	87.7	
plutonium-239	alpha	5.1	24,110	
plutonium-240	alpha	5.1	6,537	
americium-241	alpha	5.5	432	strong gamma emitter*

* With the exception of americium-241, all of these radionuclides are weak gamma emitters.

As Table 3-3 shows, the half-lives of the uranium isotopes and transuranic elements vary greatly. The fact that the half-lives of the uranium isotopes are all longer than the half-life of plutonium-239 and the fact that over hundreds of thousands of years the decay products of uranium-238 will continue to build up resulting in an increase in radioactivity, pose a challenge for long-term management of depleted uranium that has not been addressed adequately by the regulatory agencies.

DOE's Proposed Action for the Disposition of DU as Waste

On January 25, 1996, the DOE issued a Notice of Intent (NOI) to prepare a Programmatic Environmental Impact Statement (PEIS). In the NOI, the DOE presented six "reasonable alternatives" for addressing the long-term management and use of depleted uranium hexafluoride. The alternatives are:

1. "no-action" (a continuation of the current management program of on-site storage of DUF_6 in cylinders);
2. retrievable storage in the UF_6 form;

3. retrievable storage in the oxide form;
4. use as radiation shielding after conversion to metal;
5. use as radiation shielding after conversion to oxide;

   and, if DUF_6 is declared a waste,

6. disposal in oxide form in drums placed in either engineered trenches, below-ground concrete vaults, or mines.

In its alternative relating to depleted uranium as waste, the DOE does not specify under which low-level waste category it would be classified. Disposal in engineered trenches corresponds to an erroneous classification of DU as Class A low-level radioactive waste. The other two disposal options also fail to take into account that DU is essentially similar to transuranic waste in all aspects but its name. For example, putting depleted uranium in mines in no way replicates replacing the original material that was removed from the ground. As Table 1 shows, DU in the oxide form is 85 times more radioactive than typical 0.2 % uranium ore. Disposing of DU in this manner is analogous to putting transuranic waste in the ground, and TRU waste qualifies for deep geologic disposal.

IEER's Recommendations

IEER makes the following recommendations for the long-term management of depleted uranium:

- DU should be declared a waste and reclassified to reflect the fact that, for all practical purposes, the properties of DU are the same as the properties of TRU waste.
- Like TRU waste, classification of DU should require deep geologic disposal under the rules specified in 40 CFR 191 but allowing for full in-growth of radium-226.
- In the interim, DUF_6, which makes up most of the stockpile, should be converted to an oxide form in order to greatly reduce the hazards of storage. Conversion should be done with careful attention to health and environmental protection.

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2. Transuranic wastes are those which contain elements with atomic numbers (number of protons) greater than 92 (the atomic number of uranium), half-lives greater than 20 years, and concentrations greater than 100 nanocuries per gram.

3. A nanocurie is a billionth of a curie.

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