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Uranium Enrichment

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

BY ARJUN MAKHIJANI, LOIS CHALMERS, AND BRICE SMITH

Editor's Note: *News headlines about Iran's nuclear activities are the latest reminder that uranium enrichment is an important subject. This issue of SDA seeks to invigorate an informed debate by providing information and analysis about the status and process of uranium enrichment.*

The following article discusses how uranium enrichment works, types of enrichment technology, and some relevant history. The table on pages 8 and 9 summarizes the state of uranium enrichment facilities around the world. Test your knowledge about uranium enrichment with the Atomic Puzzler on the back page (you could win a prize!).

The article, table, and puzzler are based on Uranium Enrichment: Just Plain Facts to Fuel an Informed Debate on Nuclear Proliferation and Nuclear Power, *an October 2004 report prepared by IEER for the Nuclear Policy Research Institute. References can be found in the report, which is on IEER's web site at www.ieer.org/reports/uranium/enrichment.pdf.*

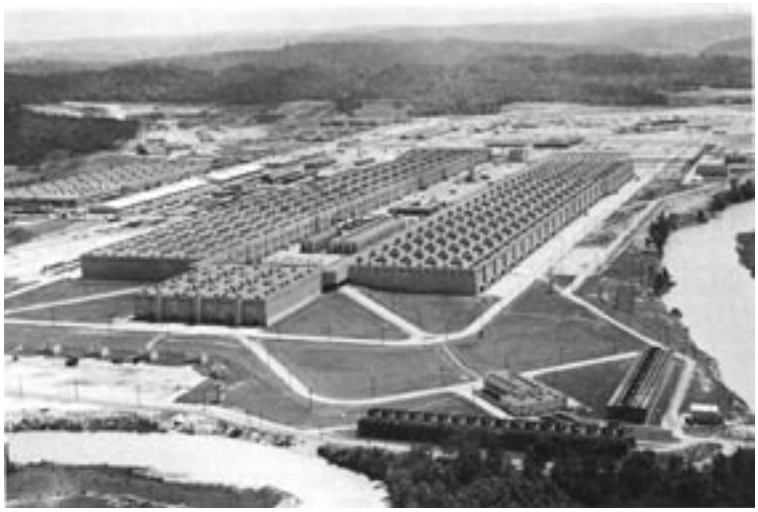

PHOTO: DEPARTMENT OF ENERGY; TAKEN FROM VINCENT C. JONES, "MANHATTAN: THE ARMY AND THE ATOMIC BOMB" (Washington, DC: Center of Military History, United States Army, 1985), p. 170.

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.*

The knowledge and ability to enrich uranium for either nuclear power or nuclear weapons are quite widespread. In many ways, the horse has already left the barn when it comes to uranium enrichment techniques. This is a particularly serious concern in light of proposals that would expand the future use of nuclear power around the world over the coming decades.

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 roughly nine to ten times greater than that currently operating in the United States would be required. If just one percent of that capacity was instead used to manufacture highly enriched uranium (HEU), then enough HEU could be produced every year to make between 175

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ESSAY

Gorbachev and the U.S. People

Uncelebrated Victories in the Struggle for the Elimination of Nuclear Weapons

BY ARJUN MAKHIJANI[1]

Former Soviet President Mikhail Gorbachev is justly famous for inaugurating *demokratizatsiya* and *glasnost* in the Soviet Union in the mid-1980s. His steadfast support for non-violence gave the people of Eastern Europe and in the Soviet Union a chance for open discourse about government, trust, democracy, and freedom. President Gorbachev, in partnership with Presidents Ronald Reagan and George H.W. Bush, gave hope to people everywhere that the world may get rid of nuclear weapons.

But this essay is about what Mikhail Gorbachev is less known for. His actions also created conditions for a special *demokratizatsiya* and *glasnost* on nuclear weapons related questions *in*

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and 310 nuclear weapons. With an expanded trade in the specialized materials required to build and operate gas centrifuge and other enrichment plants that would accompany an increase in nuclear power, illicit sales and diversion of supposedly "peaceful" technologies will become harder to identify.

Focusing on countries that are currently making headway in efforts that could support a nuclear weapons program (such as Iran) is important, but 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 as part of an effort to expand the use of nuclear power. In other words, we are wise to not ignore those countries with existing, and advanced, nuclear weapons and nuclear power programs, their significant proliferation potential, and their less than stellar proliferation track record.[1] 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 full scale uranium enrichment facilities that have been used for producing low enriched uranium (LEU) for commercial power reactor fuel.

In addition to the five acknowledged nuclear weapons states, only three countries have uranium enrichment facilities that have been used for producing significant quantities of commercial power reactor fuel. There are a number of others, however, that have pursued enrichment technologies and some of them are known or thought to have used their enrichment capability for military purposes. The table on pages 8 and 9 summarizes the current information that is available regarding the state of uranium enrichment facilities around the world.

Pakistan, one of the countries known to have produced nuclear weapons outside the NPT, to which it is not a signatory, has facilities that have enriched HEU for military applications. South Africa is also known to have manufactured nuclear weapons using enriched uranium from its own facilities. 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). North Korea, which withdrew from the NPT in January 2003 without providing the required three month notification, is widely suspected to have produced a small number of nuclear weapons using plutonium; questions remain open over North Korea's possible pursuit of a uranium enrichment program as well.

Uranium

There is one element that occurs in nature that has been the raw material for nuclear bombs: uranium, chemical symbol U.[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.

Natural uranium (i.e., that which is mined from the earth) occurs as a mixture of three different isotopes—that is, atoms with three different atomic weights that have virtually the same chemical properties but different nuclear properties. These isotopes are uranium-234,

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uranium-235, and uranium-238. Uranium-234 is a highly radioactive trace component found in natural uranium. Uranium-235 is the only fissile material that occurs in nature in significant quantities. Uranium-238 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.

Some characteristics of the three isotopes found in natural uranium are summarized in the table below. Since U-234 is such a tiny portion of the mass of natural uranium and because it is not useful in any significant applications, this article will focus almost exclusively on uranium's two other isotopes, U-235 and U-238.

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 (the light water reactor), 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 to sustain a reaction.

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 is just too small to enable a growing "super-critical" chain reaction to occur within a time short enough to create an explosion. Uranium must have a minimum of about 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,

TABLE 1: SUMMARY OF URANIUM ISOTOPES

Isotope	Mass percent in natural uranium	Radioactivity percent in natural uranium	Half-Life
Uranium-238 (U-238)	99.284	47.9	4.46 billion years
Uranium-235 (U-235)	0.711	2.3	704 million years
Uranium-234 (U-234)	0.0055	49.8	245,000 years

requiring large 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 because it is generally less well-guarded, often located in cities or on university campuses. Unlike irradiated reactor fuel, unirradiated HEU does not have a radioactivity barrier.

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.

Uranium enrichment

Since all isotopes of uranium have virtually the same chemical properties, increasing the proportion of uranium-235 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 more than one 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 process 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). Additional details about enrichment processes are discussed below, under the section called Enrichment technologies.[4]

The capacity of a uranium enrichment facility to increase the percentage of U-235 is given by units known as kilogram Separative Work Units (SWUs, pronounced "swooze"). Production level facilities typically have capacities that range from a few hundred to several thousand metric ton SWU per year (One MTSWU = 1,000 SWU). The Separative Work Unit is a complex unit that

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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.[5]

Globally, gas centrifuges are the most commonly used technology today for enriching uranium.

The number of SWUs 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 (kWh) of electricity per SWU while gas centrifuge plants require just 50 to 60 kWh of electricity per SWU.

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 per 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, for instance) then the enrichment process would consume roughly 3 to 4 percent of the electricity generated by the reactor.[6] 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 percent of the electricity generated by the nuclear plant during the year.

In addition to the kilogram Separative Work Units, another important parameter to consider is the mass of natural uranium that is needed in 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. The amount of natural uranium needed will decrease with decreasing levels of U-235 that are allowed to end up in the depleted uranium.

For example, in the enrichment of LEU for use in a light water reactor, it is typical for the enriched stream to ultimately contain 3.6 percent U-235 (as compared to 0.71 percent in natural uranium) and for the depleted stream to contain 0.2 to 0.3 percent U-235. In order to produce one kilogram of this LEU, it would require approximately 8 kilograms of natural uranium and 4.5 SWU if the depleted uranium stream was allowed to have 0.3 percent U-235. On the other hand, if the depleted stream had only 0.2 percent U-235, then it would require just 6.7 kilograms of natural uranium, but about 5.7 SWU of enrichment.

In order to produce one kilogram of highly enriched uranium (i.e. uranium containing 90 percent U-235), it would require more than 193 SWU and nearly 219 kilograms of natural uranium if the depleted uranium contained 0.3 percent U-235. It would require nearly 228 SWU and more than 176 kilograms of natural uranium if the depleted stream contained 0.2 percent U-235.

Table 2 summarizes the inputs (natural uranium and enrichment services) that would be needed to produce one kilogram of LEU and one kilogram of HEU under both the 0.2 percent and 0.3 percent U-235 depleted uranium stream scenarios.

Because the required amount of natural uranium and the required number of SWUs during enrichment change in opposite directions for a given level of enrichment, 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 (i.e. will choose to use more natural uranium and less SWUs). On the other hand, if natural uranium is relatively more expensive and enrichment is less so, they would choose the opposite.

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 13,700 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.

TABLE 2: INPUTS REQUIRED FOR PRODUCING ONE KILOGRAM OF LOW-ENRICHED URANIUM AND ONE KILOGRAM OF HIGHLY ENRICHED URANIUM

	Low-enriched uranium (LEU)		Highly enriched uranium (HEU)	
	Natural uranium	*Enrichment services*	*Natural uranium*	*Enrichment services*
If depleted uranium stream contains 0.3 percent U-235	8.2 kg	4.5 SWU	219 kg	193 SWU
If depleted uranium stream contains 0.2 percent U-235	6.7 kg	5.7 SWU	176 kg	228 SWU

LEU=uranium containing 3.6 percent U-235, typical for use in a light water reactor.
HEU=uranium containing 90 percent U-235, typical for use in a nuclear weapon.
SWU=kilogram Separative Work Units
kg= kilograms

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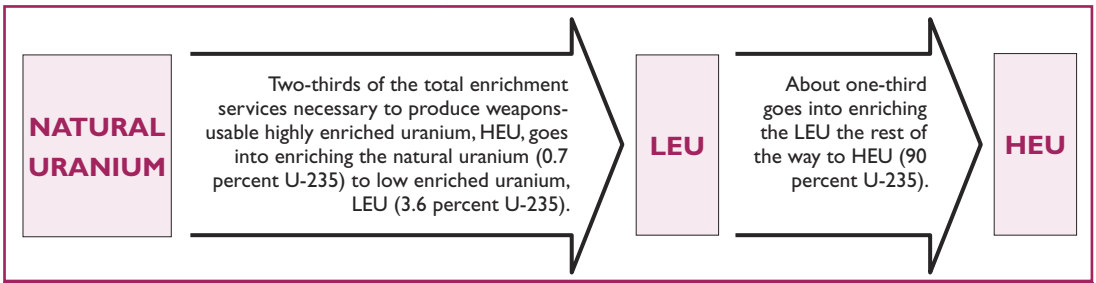

Enrichment services required to make highly enriched uranium from natural uranium.

If, instead of starting with natural uranium, low enriched uranium (3.6 percent U-235) was used as the feed material for making HEU, 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. This means that just 1.6 tons of LEU—less than one tenth of the amount needed annually to fuel a single 1,000-megawatt reactor—would be enough to yield the HEU required to assemble a Hiroshima-style bomb if it was further enriched. So, approximately two-thirds of the total enrichment services necessary to produce the weapons-usable HEU goes into enriching the uranium from natural uranium (0.7 percent U-235) to LEU (3.6 percent U-235), while only about one-third goes into enriching the LEU the rest of the way to HEU (90 percent U-235), as shown in the diagram above.

Thus, stockpiles of low enriched uranium, if maintained in a form suitable for enrichment (i.e., as uranium hexafluoride), can provide the base material to more easily and more rapidly manufacture highly enriched uranium for use in nuclear weapons. This is one of the critical proliferation risks regarding the spread of enrichment technologies as part of the spread of nuclear power.

Enrichment technologies

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, in part, to enrich 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 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 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 on page 6.

The difference in mass, and therefore velocity, between the UF_6 molecules containing either U-235 or U-238 is very small, and so thousands of such stages are needed in order to enrich commercial or militarily significant 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 the cover photograph. Two of the diffusers used in the enrichment process are shown in figure 3 on page 7.

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

In addition to requiring a large amount of electricity during operation, the compressors in the gaseous 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

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(CFCs) such as the coolant CFC-114 (often referred to simply as Freon or 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 United States is implementing through the 1990 Amendments to the Clean Air Act.

As a result of these commitments, the manufacture of Freon in the United States ended in 1995 and its emissions to the air in the United States from large users fell by nearly 60 percent between 1991 and 2002. The emissions from the Paducah gaseous diffusion plant, however, have remained virtually constant over this time, falling just over 7 percent between 1989 and 2002. In 2002, the Paducah enrichment plant emitted more than 197.3 metric tons of Freon into the air through leaking pipes and other equipment. This single facility accounted for more than 55 percent of all airborne releases of this ozone depleting CFC from all large users in the entire United States in 2002.

Due to the lack of additional manufacturing of Freon since 1995, the U.S. Enrichment Corporation[7] 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 (i.e. soil samples) that could conclusively show the presence of enriched uranium.

Gas Centrifuge

Globally, gas centrifuges are the most commonly used technology today for enriching uranium. The technology was considered in the United States 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

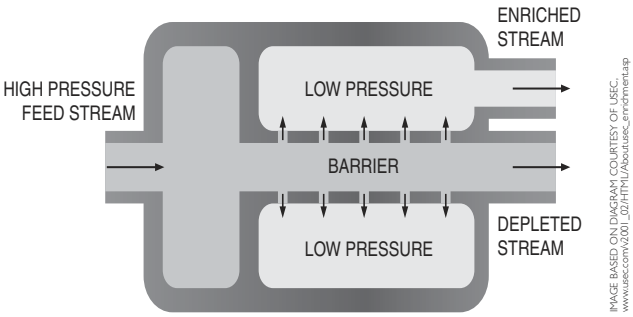

Figure 1: Schematic diagram of a single stage in a gaseous diffusion plant. *The darker colors represent the UF_6 molecules that contain the heavier U-238 atoms, while the lighter colors represent gas molecules that contain the lighter U-235. After each stage, the gas that moves to the low pressure side of the barrier (i.e. the downstream side) has a slightly higher percentage of U-235 than the stage before.*

commercial nuclear fuel.

The centrifuge is a common technology used routinely in a variety of applications such as separating blood plasma from the heavier red blood cells. The spin cycle of a clothes washing machine works on the centrifuge principle. In the uranium 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 having to be shut down for 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 that is enriched in U-235 near the center is driven towards the bottom. These two streams (one enriched and one depleted) can then be extracted from the centrifuge and fed to adjoining stages to form a cascade just as described with the diffusers in the gas diffusion plants. A schematic diagram of such a centrifuge is shown in Figure 2 on page 7.

Like the gaseous diffusion process, uranium enrichment via gas centrifuge requires thousands to tens of thousands of stages to enrich commercially or militarily significant quantities of uranium. In addition, like the gaseous 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 of the gas centrifuge over the

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gaseous diffusion process 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.

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. Therefore, enriching enough HEU in one year to manufacture a nuclear weapon like that dropped on Hiroshima would require between 3,000 and 7,000 centrifuges. Such a facility would consume 580,000 to 816,000 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 1,000 to 3,000 centrifuges and 193,000 to 340,000 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 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.

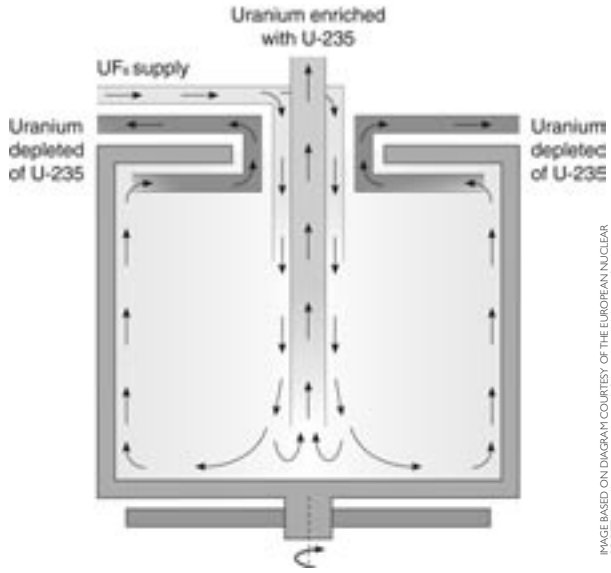

IMAGE BASED ON DIAGRAM COURTESY OF THE EUROPEAN NUCLEAR SOCIETY; http://www.euronuclear.org/info/encyclopedia/g/gascentrifuge.htm

Figure 2 : 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.*

PHOTO BY FRANK HOFFMAN, DEPARTMENT OF ENERGY; TAKEN FROM DARRELL D. EBBING AND STEVEN D. GAMMON, "GENERAL CHEMISTRY" 6th ed. (Boston: Houghton Mifflin, 1999), p. 215.

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

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 a gaseous diffusion plant, which was also located at the Oak Ridge facility. The use of this type of facility, shown in Figure 4 on page 10, was discontinued shortly after the war because it was found to be very expensive and inefficient to operate.

Iraq pursued this technique in the 1980s as part of its effort to produce HEU, because of its relative simplicity in construction, but it was successful in producing only small amounts of medium enriched uranium (just above 20 percent).

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 (the curved section of the calutron, the large O-shaped device in the middle of the picture in Figure 4) the beam of ionized uranium atoms 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.

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Uranium Enrichment Worldwide

The table below summarizes the current available information regarding the state of uranium enrichment facilities around the world. It includes the type of process the plant utilizes, its enrichment capacity and current operational status, and other information. The table is organized according to country and by groups, including declared nuclear weapons states (China, France, Russia, United Kingdom, United States), nuclear weapons states that are not signatories of the Nuclear Non-Proliferation Treaty (India, Israel, Pakistan), states of concern to the United States (Iran, Iraq, North Korea), and countries not suspected of having weapons ambitions at this time (Argentina, Australia, Brazil, Germany, Japan, Netherlands, South Africa, South Korea). Additional countries may have pursued laboratory-scale experiments for uranium enrichment.

Two things must be kept in mind when examining this table. First, the 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 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 provides a significant example of illicit proliferation of enrichment technology conducted at least in part by private individuals.

Second, there is, even for the known facilities, often conflicting and contradictory information available regarding the current status and capacity. When possible, the conflicts in information are noted, but 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 representative of the estimated production capacity of the listed facilities.

The table is based on Table 2 in the October 2004 IEER report, *Uranium Enrichment: Just Plain Facts to Fuel an Informed Debate on Nuclear Proliferation and Nuclear Power.* The main sources for the table include information complied by the International Atomic Energy Agency as well as by a number of non-governmental organizations recognized for their significant work in this area. References can be found in the report, which is on IEER's web site at www.ieer.org/reports/uranium/enrichment.pdf.

Number of facilities	Process / Scale[1]	Current status / Nominal capacity (in Metric Ton Separative Work Units per year)
Declared Nuclear Weapons states		
China[2]		
3	Gaseous diffusion / Commercial	One plant being decommissioned. One plant completed in the 1970's / >200 MTSWU/a.
3	Centrifuge / Commercial	One plant under construction / 500 MTSWU/a. The next construction phase will create another plant. Two plants started up in 1996 and 1998, producing LEU under IAEA safeguards / 500 MTSWU/a.
1	Gaseous diffusion / Laboratory	Not given.
1	CRISLA	Not given.
1	Possible enrichment facility for weapons-grade uranium	Not given.
France		
2	Gaseous diffusion / Commercial	One plant started in 1979 / 10,800 MTSWU/a. One plant being decommissioned / 0 MTSWU/a as given by IAEA.
1	Centrifuge / Commercial	Planned / 7,500 MTSWU/a.
1	Chemical Exchange / Pilot Plant	Shut down 1988 / 0 MTSWU/a as given by IAEA.
2	Laser (SILVA) / Laboratory	One shut down 2003 / 0 MTSWU/a as given by IAEA. One possibly shut down, possibly under study / 0 MTSWU/a as given by IAEA.
Russia[3]		
4	Centrifuge / Commercial[4]	One started up in 1949 / 7,000 MTSWU/a. One started up in 1950 / 4,000 MTSWU/a. One started up in 1954 / 1,000 MTSWU/a. One started up in 1964 / 3,000 MTSWU/a.

Number of facilities	Process / Scale[1]	Current status / Nominal capacity (in Metric Ton Separative Work Units per year)
Iraq[5] (continued)		
2	EMIS / Commercial	One plant "partially operational until damaged by Coalition air attack (1991); EMIS-related installations and equipment subsequently destroyed by IAEA." Other plant "under construction until damaged by Coalition air attack (1991); EMIS-related installations and equipment subsequently destroyed by IAEA." 0 MTSWU/a.
North Korea[6]		
1	Uranium Milling Facility and Suspected Uranium Enrichment Facility	Not given.
2	Underground Suspected Nuclear Facilities	Not given.
1	Laser Research Institute	Not given.
1	Suspected Uranium Enrichment Facility	Not given.
Additional states, Commercial or research programs		
Argentina		
1	Gaseous diffusion / Pilot Plant	Startup before 1983, standby 1990 / 20 MTSWU/a.
1	Gaseous diffusion / Commercial	Under construction (planning or construction possibly started in 1997) / 100 MTSWU/a.
Australia		
1	Laser (SILEX) / Laboratory	Startup 1992 (stage 2 is expected to be complete in late 2004 or early 2005; stage 3 involves construction and operation of a Pilot Plant, probably in the U.S.) / 0 MTSWU/a as given by IAEA.

United Kingdom		
1	Centrifuge / Commercial	Startup 1972 / 2,300 MTSWU/a.
1	Gaseous diffusion / Commercial	Decommissioned.
United States		
3	Gaseous diffusion / Commercial	One started up in 1954 and was updated in the 1970s / 11,300 MTSWU/a. One started up 1956, was updated in the 1970s, shut down in 2001, and now on stand by / 7,400 MTSWU/a. One started up in 1945, shut down in 1985.
3	Centrifuge / Commercial	One is planned / 3,500 MTSWU/a by 2010. One is proposed, projected for 2010 or 2011 / 3,000 MTSWU/a. One has been deferred (license application withdrawn).
1	AVLIS / Laboratory	Started up 1991, shut down 1999.
1	Centrifuge / Pilot Plant	To begin operating in 2005 / 0 MTSWU/a as given by IAEA.
Nuclear weapons states, not signatories of the NPT		
India		
2	Centrifuge / Pilot Plant	One started up 1990 / estimated at <3 MTSWU/a. One completed 1985 / capacity not given.
1	Laser / Laboratory	Startup early 1980s / capacity not given.
1	Laser / Pilot Plant	Startup 1993 / capacity not given.
Israel		
1	Laser and gas centrifuge / Laboratory & pilot plant	Not given.
Pakistan		
1	Centrifuge / Commercial	Startup 1984 / 5 MTSWU/a (the IAEA reports this will be expanded to approximately 15 MTSWU/a).
2	Centrifuge / Laboratory	Not given. One operating. Other, operational status unknown.
1	Not given	Under construction in late 1990s?
States of Concern to the U.S. Government		
Iran		
1	Centrifuge / Commercial	To startup early 2005 / 250 MTSWU/a estimate.
1	Centrifuge / Pilot Plant	Started up August 2003 / capacity not given, will hold 1,000 centrifuges.
1	?	Not given. A possible enrichment site.
2	Centrifuge?	Not given. One is a suspected enrichment site. One is an alleged uranium centrifuge research program.
1	Lasers or Centrifuge?	Not given. A suspected enrichment site.
Iraq[5]		
1	EMIS / Prototype-scale	"Operational until damaged by Coalition air attack (1991)" / 0 MTSWU/a.
2	Centrifuge / Prototype-scale	One plant's operations relocated in 1987; other plant's operations halted at the outset of the 1991 Gulf War / 0 MTSWU/a.
1	Chemical exchange isotope separation method / Laboratory	"Operational until damaged by Coalition air attack (1991)" / 0 MTSWU/a.

Brazil		
1	Centrifuge / Laboratory	Startup 1992 / 5 MTSWU/a.
2	Centrifuge / Pilot Plant	One plant started up 1998 / 4 MTSWU/a. One plant started up 1982 / capacity not given.
1	Centrifuge / Commercial	"Ultracentrifuge" under construction, 2004 startup planned / 120 MTSWU/a (ultimately to be 200 MTSWU/a).
1	Laser (AVLIS) / Laboratory	Startup 1981 / 0 MTSWU/a as given by the IAEA.
2	Jet Nozzle / Pilot Plant	One plant started up 1979, shut down 1989, being decommissioned / 0 MTSWU/a as given by IAEA. One plant cancelled.
1	Centrifuge	Proposed / capacity not given.
Germany		
1	Centrifuge / Commercial	Startup 1985 / 1,800 MTSWU/a.
1	Centrifuge / Laboratory	Startup 1964 / 0 MTSWU/a.
1	Jet Nozzle / Pilot Plant	Decommissioned.
Japan		
1	Centrifuge / Commercial	Startup 1992 / 1,050 MTSWU/a.
2	Centrifuge / Pilot Plant	One plant started up in 1989, other in 1979, both shut down 2004 and being dismantled.
1	Chemical Exchange / Pilot Plant	Started up 1986, shut down 1991.
1	Laser (MLIS) / Laboratory	Started up 1991, shut down 2003 / 0 MTSWU/a, as given by IAEA.
1	Laser (AVLIS) / Laboratory	Started up 1987, shut down 2005 (planned), decommissioning / 0 MTSWU/a, as given by IAEA.
Netherlands		
1	Centrifuge / Commercial	Startup 1973 / 2,200 MTSWU/a.
South Africa		
1	Laser (MLIS) / Pilot Plant	Startup 1995, shut down 1998.
1	Jet Nozzle / Pilot Plant	Startup 1978, shut down 1990, decommissioning.
1	Helicon / Commercial	Startup 1986, shutdown 1996, decommissioning.
South Korea		
1	Laser (AVLIS) / Laboratory	Experiments performed in early 2000[7] / capacity not given.

Acronyms

AVLIS: Atomic Vapor Laser Isotope Separation, known as SILVA in French
CRISLA: Chemical Reaction by Isotope Selective Laser Activation
EMIS: Electromagnetic Isotope Separation Method
HEU: Highly enriched uranium
IAEA: International Atomic Energy Agency
LEU: Low enriched uranium
MLIS: Molecular Laser Isotope Separation
MTSWU/a: Metric Ton Separative Work Unit per annum
SILEX: Separation of Isotopes by Laser Excitation
SILVA: Séparation Isotopique par Laser de la Vapeur Atomique d'uranium, known as AVLIS in English

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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 electromagnetic separation 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 South African 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 kilograms of uranium enriched to greater than 80% for military use. In early 1990, South African President FW 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 became a party to the NPT and just before submitting to inspections and safeguards by the International Atomic Energy Agency.

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.

PHOTO COURTESY OF THE MANHATTAN PROJECT HERITAGE PRESERVATION ASSOCIATION, PHOTO BY ED WESTCOTT, U.S. ARMY CORPS OF ENGINEERS.

Figure 4: The Y-12 electromagnetic separation plant built at Oak Ridge, Tennessee, during the Manhattan Project. *Devices like this one, also referred to as a calutron, were used, in part, to enrich the uranium for the bomb that was dropped by the United States on Hiroshima.*

The jet nozzle/aerodynamic separation 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.

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 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 con-

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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 The Monterey Institute's Center for Nonproliferation Studies reports that "The Soviet Union stopped production of highly enriched uranium for weapons by 1989."
4 All the Russian enrichment plants started as gaseous diffusion plants but were upgraded with gas centrifuges beginning in the 1960's. The first three plants listed are involved in downblending HEU to LEU under the US-Russian HEU Deal.
5 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 led invasion of Iraq toppled the government, all Iraqi facilities were shut down. Quoted items are from Carnegie Endowment for International Peace reports.
6 We list possible sites. This is very uncertain information.
7 According to a September 2, 2004 Reuters report, the South Korean government stated that "all facilities and the uranium were destroyed immediately after the experiments."

taining U-235, which can then be separated from those molecules containing U-238 that remain unaffected by the lasers. AVLIS was pursed 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. However, some work does continue on possible research facilities using these laser techniques for isotopic separation of uranium as well as other radionuclides such as plutonium.

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 processes were developed by the French and the Japanese governments. 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 a small scale while some, like AVLIS, have gone significantly further along in the development process necessary to scale them up to production level facilities. The potential for these alternative technologies to be used for enriching uranium in a clandestine program, however, remain a concern, particularly 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 uranium enrichment for nuclear power as well as for potential nuclear weapons proliferation.

1 For instance, see "The 'Usable' Nuke Strikes Back" in SDA vol. 11 no. 4, online at www.ieer.org/sdafiles/vol_11/sda11-4.pdf; "The Cheney Energy Plan: Technically Unsound and Unsustainable" in SDA vol. 9 no. 4, online at www.ieer.org/sdafiles/vol_9/9-4/cheney.html; "Plutonium End Game: Stop Reprocessing, Start Immobilizing" in SDA vol. 9 no. 2, online at www.ieer.org/sdafiles/vol_9/9-2/puend.html; and, SDA vol. 8 no. 3, online at www.ieer.org/sdafiles/vol_8/8-3/index.html.

2 Thorium-232, which is also naturally occurring, can be used to make bombs by first converting it into U-233 (a uranium isotope virtually non-existent in nature) 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.

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.

4 The enrichment process follows uranium mining, milling and conversion. Traditionally, uranium has been extracted from open-pits and underground mines. Alternative techniques such as in-situ leach mining, in which solutions are injected into underground deposits to dissolve uranium, have become more widely used. Mining and milling operations have disproportionately affected indigenous populations around the globe. Milling (refining) extracts uranium oxide (U_3O_8) from ore to form yellowcake, a yellow or brown powder that contains about 90 percent uranium oxide. In the United States, the total volume of mill tailings accounts for more than 95 percent of the volume of all radioactive waste from all stages of the nuclear weapons and power production cycle. 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. The conversion process converts yellowcake to uranium hexafluoride (UF_6).

5 SWUs are measured in kilograms, though what SWUs really measure is the effort it takes to increase the percentage of U-235 in a stream of uranium to specified levels.

6 This calculation assumes that the nuclear plant operates at full power for approximately 80 to 90 percent of the year.

7 USEC is the operator of the two gaseous diffusion plants in the United States, one at Piketon in Ohio (which no longer enriches uranium commercially) and the other at Paducah in Kentucky. USEC was created as a government corporation under the Energy Act of 1992 and privatized by legislation in 1996. USEC wants to build gas centrifuge facilities at Piketon; the U.S. Nuclear Regulatory Commission this year issued USEC a license to construct and operate the so-called Lead Cascade facility at Piketon to test the gas centrifuge process for the U.S. market. Another company, Louisiana Energy Services (LES), wants to build a commercial gas centrifuge plant in the United States but has been met with community resistance everywhere it has proposed building one.

the United States. In turn, this caused a closure of most of the large U.S. nuclear weapons facilities in the late 1980s and early 1990s. In addition to raising the hopes of people in his own country, Gorbachev's work also lifted a fear from the hearts and minds of the people of the United States, and enabled them to look at their own nuclear weapons establishment with fresh eyes.

Gorbachev's reach

It started with the trip that Gorbachev made to Britain in December 1984, before he became General Secretary of the Communist Party of the Soviet Union. He was immediately recognized as a prospective leader of the Soviet Union. With his wife, Raisa, Mr. Gorbachev charmed Prime Minister Thatcher, known in British politics as the "Iron Lady." She said that he was a man with whom she "could do business."

After Gorbachev became General Secretary, he talked about reducing nuclear dangers and eliminating the threat of nuclear war. He abandoned the language of confrontation and replaced it with cooperation. If Margaret Thatcher could do business with him, President Reagan could too.

Gorbachev's U.K. trip opened the door for the people of the United States to do business with their own government in a manner that no one anticipated. Instead of keeping their eyes fixed on the Soviet Union out of fear, more and more people began to look more closely at the nuclear contamination in their neighborhoods. Some courageous ones had done that before, as indeed, they had in the Soviet Union. But the nuclear weapons establishment had generally been able to silence them, get lawsuits thrown out of court, and cover its own actions in rhetoric of national security and propaganda about the Soviet threat.

Starting at about the time of Gorbachev's visit to Britain and for the rest of the 1980s, the numbers of people in the United States with questions about water and air pollution, radioactive waste, and nuclear safety risks due to aging nuclear weapons plants grew rapidly. In times past, public concerns would have quickly died out. But this time, local and national media, law enforcement officials, elected legislators, congressional committees, and even the U.S. Federal Bureau of Investigation (FBI) paid more attention to environmental matters relating to nuclear weapons production than they ever had.

Certainly, it was unthinkable during the Cold War that the FBI might become involved in raiding a nuclear weapons plant to look for evidence of environmental crimes.[2] It may have been denounced as a communist plot within the U.S. government. For example, in 1954, when the Japanese fishing boat, the Lucky Dragon, became heavily contaminated with fallout for the U.S. hydrogen bomb test at Bikini, the then-Chairman of the Atomic Energy Commission falsely said that it was a Red spy boat inside the prohibited test area.[3]

People were routinely discovering that their own government had done them and their children a great deal of harm.

But this time, because of Gorbachev's refusal to use violence to suppress the hopes of the people in Eastern Europe, the zero-zero Intermediate-Range Nuclear Forces (INF) Treaty for intermediate-range nuclear missiles, and the warm relationship between Presidents Gorbachev and Reagan, the result was dramatically different. By the time the Soviet Prime Minister Nikolai Ryzhkov said in 1987, upon the signing of the INF treaty, "I do think the winter of mistrust is over," much more than the fear of the Soviet Union had lifted. The people were routinely discovering that their own government had—under cover of secrecy, with the aid of bad science, and in the frigid public fright of the Cold War—done them and their children a great deal of harm.

An Ohio story

Consider a nuclear weapons factory in southwestern Ohio, about 17 miles west of Cincinnati. It produced half a million tons of uranium metal mainly for use in U.S. plutonium reactors at Hanford and South Carolina. In December 1984 Lisa Crawford, who lives near the plant, heard that some wells in the area were contaminated with uranium. Until then, she and most others like her did not even know they were living near a nuclear weapons plant. It was called the Feed Materials Production Center and had a water tower painted in a red and white checkerboard pattern that resembled the logo of Purina, the famous pet food company. With cows grazing near it, many people thought it was a pet food plant. Others thought it produced paint because it was run by a subsidiary of National Lead Industries, which was a well-known paint-maker at the time. But few knew it was a nuclear weapons plant. It is commonly known as the Fernald plant.

People thought the Feed Materials Production Center was a pet food plant. Few knew it was a nuclear weapons plant.

In January 1985 there was uproar in this quiet part of Ohio, known for its conservative, anti-communist views. People wanted to know whose wells were contaminated. Tom Luken, the area's representative in the U.S. Congress at the time, held a meeting there. Hundreds came. Lisa found out that her well was one of polluted ones. She had a young son. She made food with water from the well, and filled her backyard pool with it. She was very upset.

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As usual, the U.S. nuclear weapons establishment said the water was quite safe and there was no need to worry. But, unlike the 1950s and 1960s and 1970s, when most people trusted such assurances, Lisa and her neighbors did not. She was afraid her child might get cancer. (Thankfully, he is well). She did three things. First, she and her husband decided they were not going to have more children, a difficult and tragic way to make such a decision. Second, she got bottled water. Third, at the end of January 1985 she filed a tort lawsuit against the corporation that ran the Fernald plant for the government on behalf of her family and 14,000 other people who lived in the area. They claimed that the company, National Lead of Ohio, had been negligent and endangered their health and damaged their property. The U.S. government defended the lawsuit and paid all the expenses.

There had been previous lawsuits regarding nuclear weapons issues. In fact, General Groves, who headed the Manhattan Project during World War II, was afraid of them as early as April 1945.[4] For example, in the 1950s, shepherds had filed a lawsuit against the government claiming that thousands of sheep had died because of fallout. But representatives of the Atomic Energy Commission falsely told the court that it was not fallout. The case was dismissed. The judge found out in 1980 and wrote that the government had been "deceptive" and "deceitful" in its presentation of the evidence in the case.[5] He reversed his decision and made one in favor of the shepherd. But the U.S. government appealed and prevailed.

Lisa's lawsuit succeeded where others had failed. Between 1985 and 1989 there was an enormous amount of local and national publicity about the Fernald plant. Lisa became a well-known figure in Ohio and other parts of the country. As part of the lawsuit, the Institute for Energy and Environmental Research was retained to do an expert assessment of radioactivity releases from the plant. In 1989, Bernd Franke and I published the first independent assessment of radioactivity releases from a nuclear weapons plant. We concluded that the nuclear weapons establishment had done poor science, entered fraudulent data into official records, been negligent in operating the plant, and violated its own rules regarding radiation safety. We also concluded that the official estimates of uranium releases from the plant were much higher than what the government and its contractors had told the public. We estimated that releases of uranium had probably been more than 300,000 kilograms since the 1950s, compared to the government's estimates in 1987 of 135,000 kilograms, revised in 1989 to 179,000 kilograms.[6]

In April 2004 I asked Lisa whether Gorbachev's becoming General Secretary and then President of the Soviet Union played a role in her thinking. She said it was not a direct influence. But she said it affected how she viewed the U.S. government's criticism of the Soviet government. She specifically mentioned the Chernobyl accident. She said that she thought then that "the United States is horrified that the Soviets did not tell us for three days but they [the U.S. government] did not tell us [about Fernald] for thirty years." It no longer worked for the U.S. government to point a finger at problems over there in the Soviet Union. It did not divert Lisa's attention from the problem she was focused on—finding out about the pollution in her own neighborhood.[7]

The government settled the lawsuit in June 1989 for $78 million. The money is mainly being used for providing medical monitoring to people. But there was another happy result. In July 1989, production at the Fernald plant was stopped forever. The combination of the Cold War winding down and the lawsuit and the scandals around radioactive pollution of air and water worked together to accomplish important progress in disarmament. The Fernald plant has been dismantled and the factory buildings have been torn down.

Tank explosion risks

June 1989 was an historic month in other ways as well. In that month the Soviet government admitted that a high-level waste tank had exploded in 1957 at Chelyabinsk-65 by filing a report about the accident with the International Atomic Energy Agency. I believe this was in response to a question about the accident that Dr. Bernard Lown had raised in a meeting in April 1989 with then-Soviet Foreign Minister Eduard Schevernadze. That, too, had big implications for people working the United States. The U.S. Central Intelligence Agency (CIA) had known about the accident since 1959. But, unlike so many other things, it took no propaganda advantage of it. Instead, it kept the matter secret, until its papers were revealed as a result of a Freedom of Information Act request by the nongovernmental organization Public Citizen in 1977. (A dissident Soviet scientist, Zhores Medvedev, had written about the accident in the West in 1976.)[8]

I suspect that the Atomic Energy Commission did not want to admit that there was also a risk of tank explosion in the United States due to hydrogen build up because the official U.S. position continued to be that things were safe even after the CIA documents became public. But when the Soviet Union officially admitted in 1989 that there had been an explosion, one result was deeper NGO and Congressional investigations into the problems in the United States. The Department of Energy established its own panel on the high-level waste tanks at the Hanford site and steps were taken to reduce explosions risks. Concern about these risks helped ensure permanent closure of the last operating plutonium separation plant at Hanford in the early 1990s.

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FBI raid on Rocky Flats

Perhaps the most dramatic event of June 1989 in this regard was the FBI raid on the Rocky Flats plant near Denver, a large scale factory for producing plutonium pits for nuclear weapons. Such a raid would have been unthinkable during the Cold War. But by 1989, there was daily publicity about safety issues in the nuclear weapons complex. There had been a Congressional investigation of human radiation experiments done by the U.S. government. More Congressional hearings were focused on health and safety. Before the mid-1980s, such hearings were mainly routine exercises to give more money for nuclear weapons establishment. The scandals multiplied.

The Deputy Energy Secretary admitted that the Rocky Flats plant had been operated as if the nuclear establishment was above the law.

In this atmosphere, federal officials in the Department of Justice based in Colorado heard that illegal burning of plutonium-containing waste may be taking place at Rocky Flats. FBI headquarters in Washington took notice and ordered the raid. The Department of Justice convened a grand jury to investigate whether the corporation that ran the plant had committed environmental crimes. Production at the Rocky Flats plant was stopped. Deputy Energy Secretary W. Henson Moore went to Denver and admitted that the plant had been operated as if the nuclear establishment was above the law.

In the late 1950s, the Rocky Flats Plant was producing about 10 plutonium pits *every day*. When production was stopped in 1989, the U.S. government fully intended to re-open it after fixing the safety and environmental problems. But Rocky Flats never re-opened. It will never again produce nuclear weapons. It has been dismantled, though the plutonium will remain for generations in the form of residual contamination.

In the course of pursuing the Cold War, the nuclear weapons establishment poisoned much of the U.S. milk supply and did nothing to protect it.

By 1989, the public feeling had grown strong that since the United States was arriving at agreements to reduce nuclear weapons, why should the people's health be put at risk to operate unsafe nuclear weapons plants? The historic events that were occurring in Eastern Europe that are so well celebrated in history books found an echo in Colorado and elsewhere. The global importance of these local events is becoming clearer today than it was then.

Uncelebrated victories

The list of local events and concerns about health and environment that added up to an immense accomplishment for the elimination of nuclear weapons is long. All U.S. plutonium and tritium production reactors were closed in the same period. The large plutonium separation plant at Hanford in Washington State was shut. The plutonium for the Nagasaki bomb was made at Hanford. Many smaller facilities were also closed. When the United States stepped down so many large nuclear weapons plants in the late 1980s and early 1990s, it fully intended to resume production. Sometimes plants were shut from one day to the next, with material still in the production lines.

The Soviet moratorium on nuclear testing that President Gorbachev initiated reverberated in the United States. The nuclear weapons establishment argued against making the moratorium into a U.S. law, but failed. (They did get the so-called stockpile stewardship program for nuclear weapons and a great deal of money for it as a consolation prize, however.) The moratorium was enacted into law and played a role in the achievement of the Comprehensive Test Ban Treaty (CTBT).

Of course, there have been severe reverses since the mid-1990s on many fronts including nuclear weapons. The U.S. Senate rejected ratification of the CTBT. The U.S. nuclear weapons establishment has created a new nuclear weapons doctrine that actually names target states, including Russia. It wants to build usable nuclear weapons called "robust nuclear earth penetrators" and mini-nukes.[9] Money for design of nuclear weapons as well as maintaining a huge U.S. arsenal is flowing at levels higher than the average of the Cold War.

But amidst this gloom there are accomplishments from the 1980s and 1990s that endure. Specifically, the U.S. nuclear weapons establishment does not have the capacity to mass manufacture nuclear bombs because Rocky Flats was the only large-scale plutonium pit manufacturing facility in the United States. Its production buildings have been torn down. The Department of Energy has proposed building a new large-scale factory for manufacturing plutonium pits, but it will take a decade or more to build. That gives peace and environmental advocates some time to organize a struggle to prevent it from being built.

Unlike during the Cold War, it is now much more difficult for the nuclear weapons establishment to get the money for such a factory. Many Congresspersons recognize it is a dangerous proliferation provocation. Local concerns are also crucial. While some want the money and jobs that a new factory would bring, many more are opposed than would have been imaginable during the Cold War, even though we are in a period that resembles it in many ways. But this time the government cannot pretend that such a plant will pose no risks. It is required

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to publish risk estimates, which indicate that, over the life of the plant with a capacity of 450 plutonium pits per year, nine workers would die from their work.[10] The nuclear weapons establishment has asked people not to worry because it is only a statistical estimate. But the public is skeptical. The idea that a little plutonium won't hurt you finds few takers.

The gains on nuclear testing are also likely to endure. The nuclear weapons establishment would like to resume testing. But this would be very difficult. During the late 1980s and the 1990s, a huge scandal emerged regarding the poisoning of much of the U.S. milk supply with iodine-131. At first, in the 1980s, it was about iodine-131 emissions from the plutonium separations plants at Hanford. But the issue grew from there. In 1997, the National Cancer Institute released a study showing that iodine-131 releases from atmospheric nuclear weapons testing at Nevada had been 130 million curies, more than 15 times greater than the releases from the Chernobyl accident. The high fallout areas were spread out all over the country from Idaho and Montana to Kansas and Iowa to New York and Vermont. In the course of pursuing the Cold War, the nuclear weapons establishment poisoned much of the U.S. milk supply and did nothing to protect it. At the same time, declassified documents revealed that the government had provided secret data to Kodak and other photographic film companies so that they could take measures to protect film from becoming fogged as a result of fallout.

Today, as the U.S. nuclear weapons establishment prepares to test again, the National Academy of Sciences is looking into whether people should be compensated due to the milk contamination and if so how many. A conservative senator, Bob Bennett, Republican from Utah, is playing a role in slowing down the rush for testing. According to his website he has proposed legislation that "will prevent the resumption of nuclear testing without approval by the Congress, extensive environmental and safety analysis, and open public involvement."[11] If this law is passed, it will be difficult or impossible for the United States to resume testing unless some other country does it first.

Enduring accomplishments

In October 1989, President Gorbachev told the world, "the Soviet Union has no moral or political right to interfere in the affairs of its East European neighbors. They have the right to decide their own fate." This opened up the arena for the people of the United States to decide the fate of U.S. nuclear weapons plants. The tradition of vigorous citizen participation in the United States re-awakened with Gorbachev's determination not to repeat the ghastly violence of the past. The combination has produced a result in reducing the nuclear weapons menace that has not been celebrated, but whose fruits we continue to enjoy.

The world is undeniably going through a difficult time; war and violence are a constant theme. But the accomplishments of mothers and fathers concerned about their children and water and milk that resulted in a shut down of production at so many nuclear weapons plants and a moratorium on nuclear testing endure. They provide us with breathing room to secure the gains of those times for posterity and to continue to push for the complete elimination of all nuclear arsenals and weapons plants.

1 Some of the research for this article was done as part of a book grant to Arjun Makhijani made by the John D. and Catherine T. MacArthur Foundation. The working title is *Science of Death, Science of Life: An Enquiry into the Contrasts between Weapons Science and Health and Environmental Science in the U.S. Nuclear Weapons Complex.*

2 See Wes McKinley and Caron Balkany, Esq., *The Ambushed Grand Jury: How the Justice Department Covered Up Government Nuclear Crimes and How We Caught Them Red Handed.* New York: Apex Press, 2004.

3 Leo Strauss, as cited in Barton C. Hacker, *Elements of Controversy: The Atomic Energy Commission and Radiation Safety in Nuclear Weapons Testing 1947–74*. Berkeley, California: University of California Press, 1994. pp. 150–151.

4 Barton C. Hacker, *The Dragon's Tail: Radiation Safety in the Manhattan Project 1942–1946.* Berkeley, California, University of California Press, 1987, p. 85.

5 International Physicians for the Prevention of Nuclear War and Institute for Energy and Environmental Research, *Radioactive Heaven and Earth: The health and environmental effects of nuclear weapons testing in, on, and above the earth.* New York: Apex Press, 1991, Chapter 4.

6 For more information on Fernald releases, see *Science for Democratic Action* vol. 5 no. 3 (October 1996). For information about flawed nuclear worker dose records, see *Science for Democratic Action* vol. 6 no. 2 (November 1997).

7 Arjun Makhijani, *Science of Death, Science of Life* manuscript, Lisa Crawford interview.

8 International Physicians for the Prevention of Nuclear War and Institute for Energy and Environmental Research, *Plutonium: Deadly Gold of the Nuclear Age.* Cambridge, MA: IPPNW Press, 1992.

9 See "The 'Usable' Nuke Strikes Back," in *Science for Democratic Action* vol. 11, no. 4 (September 2003).

10 See "Back to the Bad Old Days," in *Science for Democratic Action* vol. 11, no. 4 (September 2003).

11 Press release of U.S. Senator Bob Bennett, "Bennett Bill Halts Nuclear Testing Without Congressional Approval, Public Input," September 7, 2004, online at http://bennett.senate.gov/press/record.cfm?id=225115.

Sharpen your technical skills with Dr. Egghead's Atomic Puzzler

Answers to the following questions can be found in the main article, "Uranium Enrichment."

1. a. How much electricity (in kilowatt-hours per Separative Work Unit, or kWh/SWU) do gaseous diffusion plants use?

b. How much electricity (in kWh/SWU) do modern gas centrifuge plants use?

2. a. How much enrichment services, in SWU per year, would be required to provide enriched uranium to fuel a typical 1,000 megawatts-electric light water reactor?

b. If this enrichment was provided by a gaseous diffusion plant, what percentage of the annual electricity generated by the reactor would the enrichment process consume?

c. If the enrichment was provided by gas centrifuges, what percentage of the annual electricity generated by the reactor would the enrichment process consume?

3. a. How much HEU (in kilograms) was used in the Hiroshima bomb?

b. How much HEU is used in a bomb of more efficient design?

c. How many metric tons of natural uranium and how many SWUs of enrichment services would be required to make a Hiroshima-style bomb?

d. How many tons of LEU would be enough to yield the HEU required to assemble a Hiroshima-style bomb? How does this compare to the amount of LEU needed to annually fuel one 1,000-megawatt nuclear reactor?

4. a. What proportion of the total enrichment services necessary to produce weapons-usable HEU goes into enriching the uranium from natural uranium (0.7 percent U-235) to LEU (3.6 percent U-235)?

b. What proportion goes into enriching the LEU the rest of the way to HEU (90 percent U-235) ?

5. Typically, how much uranium-235 (as a percentage) is contained in:

a. low enriched uranium (LEU)?

b. highly enriched uranium (HEU)?

c. natural uranium?

6. True or false: The required amount of natural uranium and the required number of SWUs during uranium enrichment are directly proportional to each other for a given level of enrichment.

7. True or false: SWUs and the weight of uranium are both typically measured in kilograms, though they measure different things.

Send us your completed puzzler via fax (1-301-270-3029), e-mail (ieer@ieer.org), or snail mail (IEER, 6935 Laurel Ave., Suite 201, Takoma Park, Maryland, 20912, USA), postmarked by March 31, 2005. IEER will award a maximum of 25 prizes of $10 each to people who send in a completed puzzler (by the deadline), right or wrong. One $25 prize will be awarded for a correct entry, to be drawn at random if more than one correct answer is submitted. International readers submitting answers will, in lieu of a cash prize (due to exchange rates), receive a copy of IEER's October 2004 report, *Uranium Enrichment: Just Plain Facts to Fuel an Informed Debate on Nuclear Proliferation and Nuclear Power.*

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