Lecture 4: Nuclear Energy Basics, Part 2: Reactors and Nuclear Fuel Making

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QUESTIONS TO BE ADDRESSED:

I. **What are the basic stages of once-through uranium-based fuel cycles?**
II. **What are the most popular methods of enriching uranium?**
III. **What are the different types of nuclear reactors and how proliferation prone is each?**
IV. **What can be done with spent reactor nuclear fuel?**

Nuclear Energy & The Fuel Cycle

It is difficult to differentiate between peaceful nuclear activities and those useful to produce nuclear explosive materials. This chapter is designed to explain the steps of the nuclear fuel cycle and of nuclear energy production and to spotlight those aspects that present the greatest nuclear weapons proliferation risks.

The nuclear fuel cycle can be broken down into six basic stages. There is, however, many conceivable nuclear fuel cycles. This primer covers two of the most popular ones: The once-through uranium fuel cycle (see Figure 1 below) and the closed plutonium fuel cycle (see Figure 2 below).

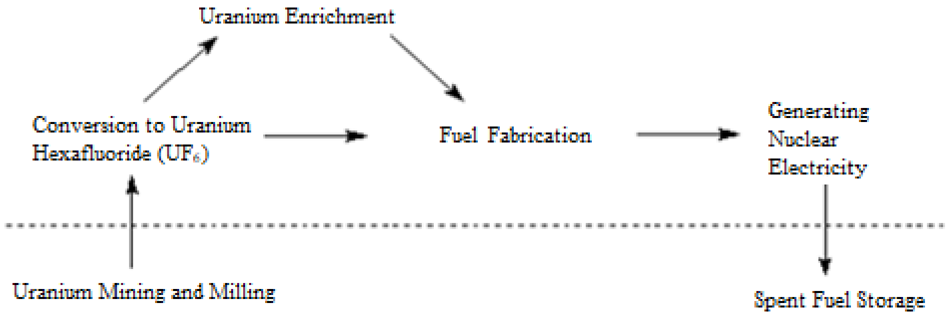

FIGURE 1
Once-Through Uranium-Based Fuel Cycle

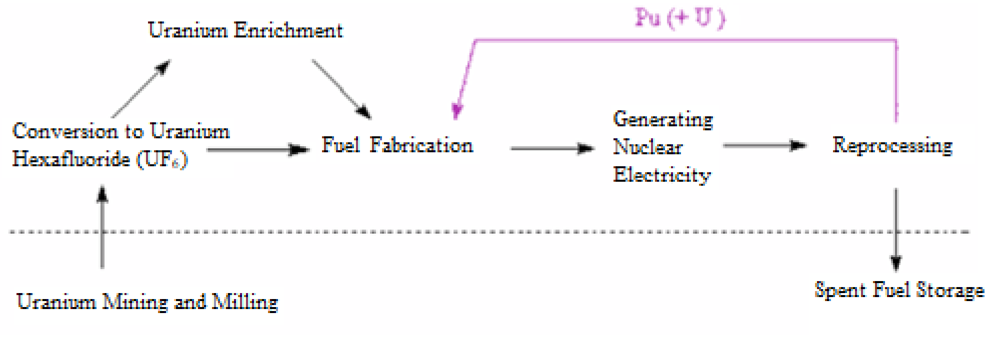

FIGURE 2
Closed Plutonium-Based Fuel Cycle

<u>Basic Stages of Once-through Uranium Based Fuel Cycles:</u>

1	Uranium Mining and Milling
2	Conversion to Uranium Hexafluoride (UF_6)
3	Uranium Enrichment
4	Fuel Fabrication
5	Generating Nuclear Electricity
6	Spent Fuel Storage

Stage 1: Uranium Mining and Milling

The first stage of the nuclear fuel cycle is extracting raw uranium ore and processing or milling it into a form that can be used to fabricate nuclear fuel. Milling concentrates the amount of recovered uranium by crushing the mined ore and using chemicals to leach the desired uranium from the surrounding material. Uranium is then processed into uranium oxide (U_3O_8), a material commonly known as yellowcake, which can then be fabricated into nuclear fuel after additional processing and enrichment.

Currently, at least nineteen countries produce uranium, but approximately two-thirds of the world's uranium supply comes from just three countries: Kazakhstan, Canada, and Australia (for the largest uranium producing states, see Figure 3).[1]

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[1] World Nuclear Association, "World Uranium Mining Production," available from https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/mining-of-uranium/world-uranium-mining-production.aspx

Uranium was once used in commonplace activities such as glass making—the presence of uranium lends a yellow-green fluorescence to the glass—glazing ceramic dishes like Fiestaware, and providing radium for medical purposes. However, now that the dangers of radioactivity are better understood, uranium is rarely used outside of nuclear energy applications.

2016 Annual Uranium Production
(t = metric tons uranium)

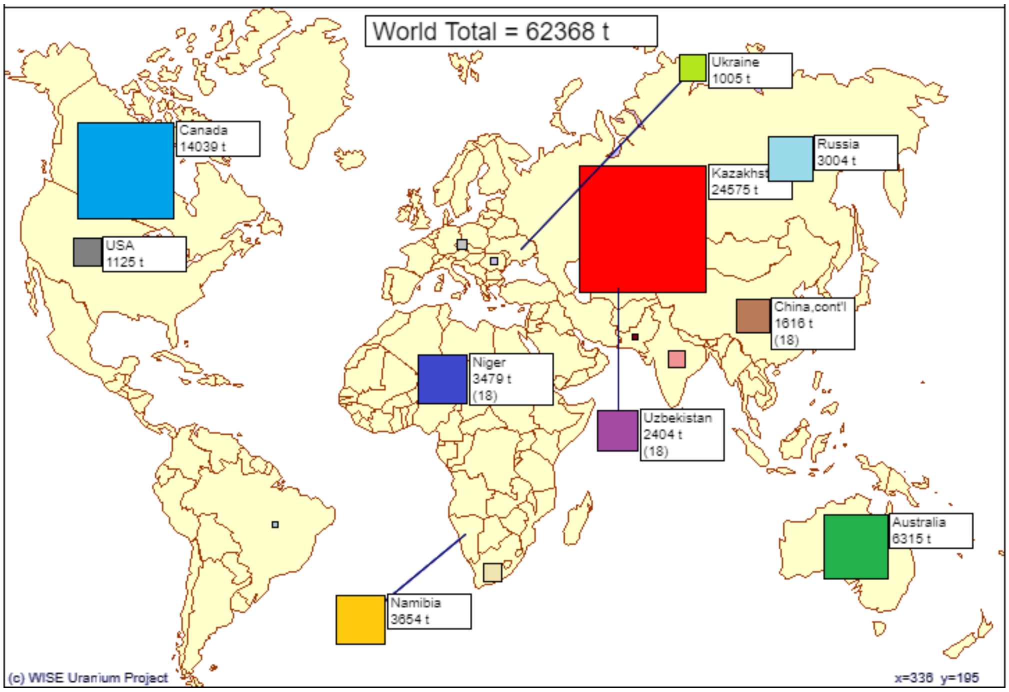


FIGURE 3
2016 Annual Uranium Production, Largest Producers
Source: [World Nuclear Association]() and [WISE Uranium project]()

There are two main methods of extracting natural uranium ore from the earth: conventional mining (using either underground shafts or open pit mines, see Figure 4) and in situ recovery (ISR, see Figure 5).

Conventional Mining

Underground	Open Pit
	
Underground mines are used to reach smaller uranium ore deposits that are located farther underground. These mines require less construction, remove less overlying and waste rock, and have a smaller environmental impact than open pit mines. Source: https://fas.org/programs/ssp/nukes/fuelcycle/index.html	Open pit mines are used to access large deposits of uranium ore that are located close to the earth's surface. This process involves the removal of large amounts of overlying and waste rock. Source: https://www.gettyimages.com/detail/news-photo/view-of-rossing-uranium-mine-in-swakopmund-on-february-11-news-photo/974219728?irgwc=1&esource=AFF_GI_IR_TinEye_77643&asid=TinEye&cid=GI&utm_medium=affiliate&utm_source=TinEye&utm_content=77643

FIGURE 4

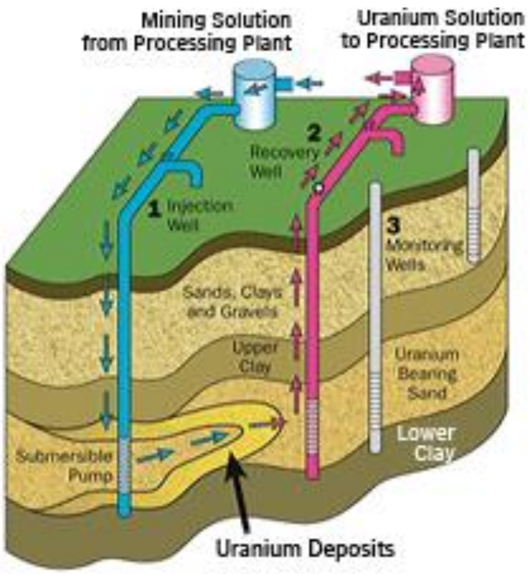
Underground and Open Pit Mining Conventional Milling

In Situ Recovery (ISR)

In situ recovery—also known as in situ leaching outside the United States or, alternatively, as solution mining—is a method of obtaining uranium ore that, unlike underground or open pit mining, does not require removing the surrounding rock. This, in turn, eliminates the need to mill the uranium in a separate step. Most uranium recovery in the United States uses ISR mining.
As described by the U.S. Nuclear Regulatory Commission

> In the in situ recovery process, injection wells (1) pump a chemical solution — typically sodium bicarbonate and oxygen — into the layer of earth containing uranium ore. The solution dissolves the uranium from the deposit in the ground, and is then pumped back to the surface through recovery wells (2) and sent to the processing plant to be converted into

uranium yellowcake. Monitoring wells (3) are checked regularly to ensure that uranium and chemicals are not escaping from the drilling area.[2]



1. **Injection Wells**
2. **Recovery Wells**
3. **Monitoring Wells**

FIGURE 5
In Situ Recovery (ISR)
Source: NRC http://www.nrc.gov/materials/uranium-recovery/extraction-methods/isl-recovery-facilities.html

During in situ recovery, the uranium is dissolved from the ore while underground, so there isn't any ore to crush like with conventional milling.

Milling

Milling concentrates the recovered uranium by crushing the mined ore and using chemicals (typically sulfuric acid) to leach the desire uranium from the surrounding material.

Yellowcake

This uranium, as mentioned before, is then processed into uranium oxide (U_3O_8), more commonly known as yellowcake (see Figure 6). This yellowcake is sent to conversion plants where it is fluorinated to produce uranium hexafluoride (UF_6), sometimes referred to as "hex." This uranium hexafluoride (UF_6) is necessary for enriching uranium.

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[2] United States Nuclear Regulatory Commission, "United States Nuclear Regulatory Commission Information Digest 20102011," available from http://pbadupws.nrc.gov/docs/ML1024/ML102460490.pdf.

FIGURE 6
U_3O_8 or Yellowcake
Source: Modified IAEA image

Stage 2: Conversion of Yellowcake to Uranium Hexafluoride (UF_6)

Yellowcake to Uranium Hexafluoride

As noted, yellowcake uranium oxide (U_3O_8), which is solid, must be converted through a number of chemical steps to uranium hexafluoride (UF_6), which is a gas. These reactions include conversion of the yellowcake into uranium dioxide (UO_2) and uranium tetrafluoride (UF_4), which is also referred to as “green salt” due to its color. The uranium tetrafluoride (UF_4) is then treated with fluorine gas (F^2), forming uranium hexafluoride (UF_6).

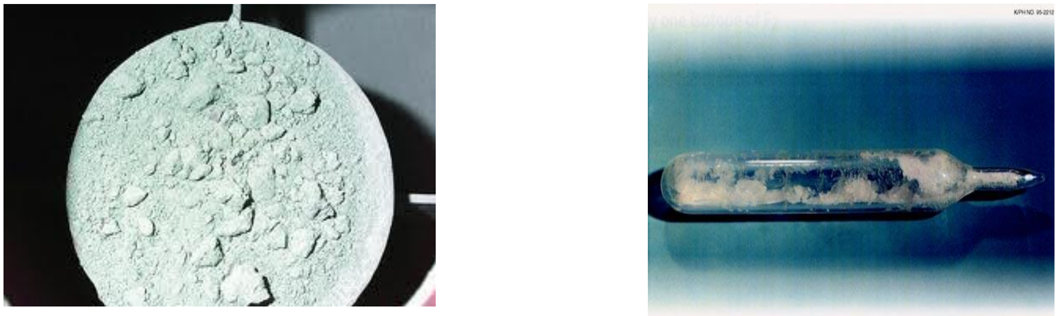


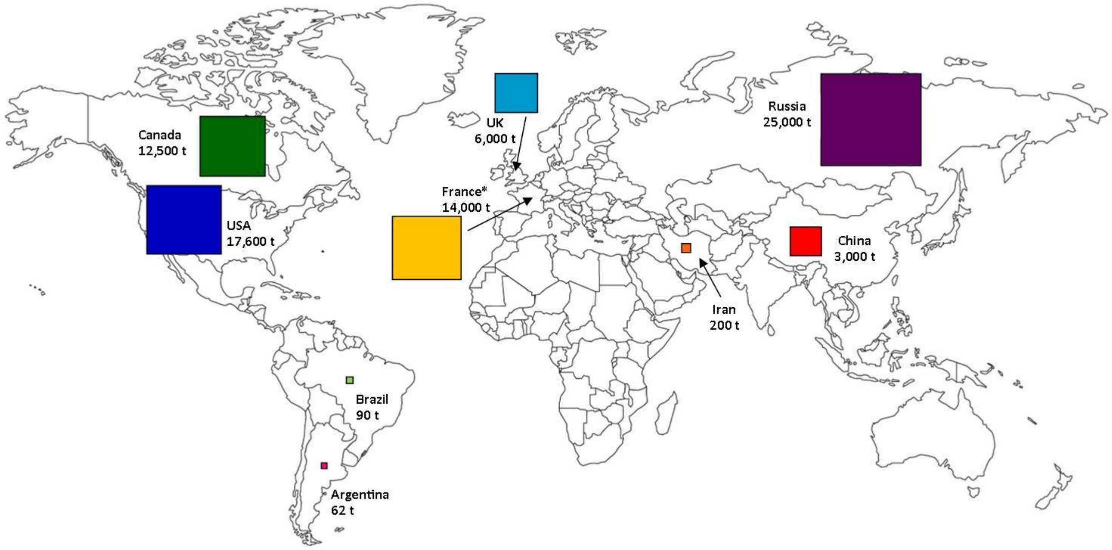
FIGURE 7
UF_4 or “Green Salt” and UF_6

UF$_6$ Conversion Facilities

Most of these uranium conversion steps are taken at UF$_6$ conversion plants, which are large. There are only a handful of these plants worldwide. These locations include the U.S., Brazil, Argentina, the UK, France, Russia, China, Iran, Israel, India, Pakistan, Japan, and North Korea (for the largest UF6 producing states, see Figure 9).

FIGURE 8
Port Hope Conversion Facility in Ontario, Canada
Source: http://www.snclavalin.com/expertise.php?lang=en&id=10

Uranium Hexafluoride (UF$_6$) Conversion Capacity
[t U/year] metric tons uranium/year



** Capacity for France excludes Comurhex II , under construction, estimated capacity of 15,000 t/year*

FIGURE 9
Sources: WISE, WNA, IAEA, ISIS, PNL, U.S. NRC

Stage 3: Uranium Enrichment

Not all reactors (e.g., heavy water reactors and graphite-moderated reactors) require enriched uranium fuel. Uranium for reactors that use un-enriched, or natural, uranium fuel is sent directly to the fuel fabrication facilities, bypassing the enrichment stage. For most other reactors, though—specifically light water reactors (LWRs) and heavy water moderated reactors (HWRs)—the uranium to fuel them must be enriched in the fissile isotope of U^{235}.

For LWRs used to generate electricity, natural uranium that only contains .7 percent U^{235} is enriched to between three and five percent in the isotope U^{235}. Uranium that is enriched below 20 percent is referred to as low enriched uranium, or LEU, to distinguish it from uranium enriched to higher levels of U^{235}, which is generally known as medium enriched uranium (MEU) and highly enriched uranium, or HEU.

The latter is used to make nuclear weapons and to fuel certain types of high performance naval and research reactors. The level of effort needed to enrich natural uranium (measured in separative work units or SWUs) to LEU (three to five percent) is roughly two thirds that needed to enrich natural uranium to HEU (see Figure 10):

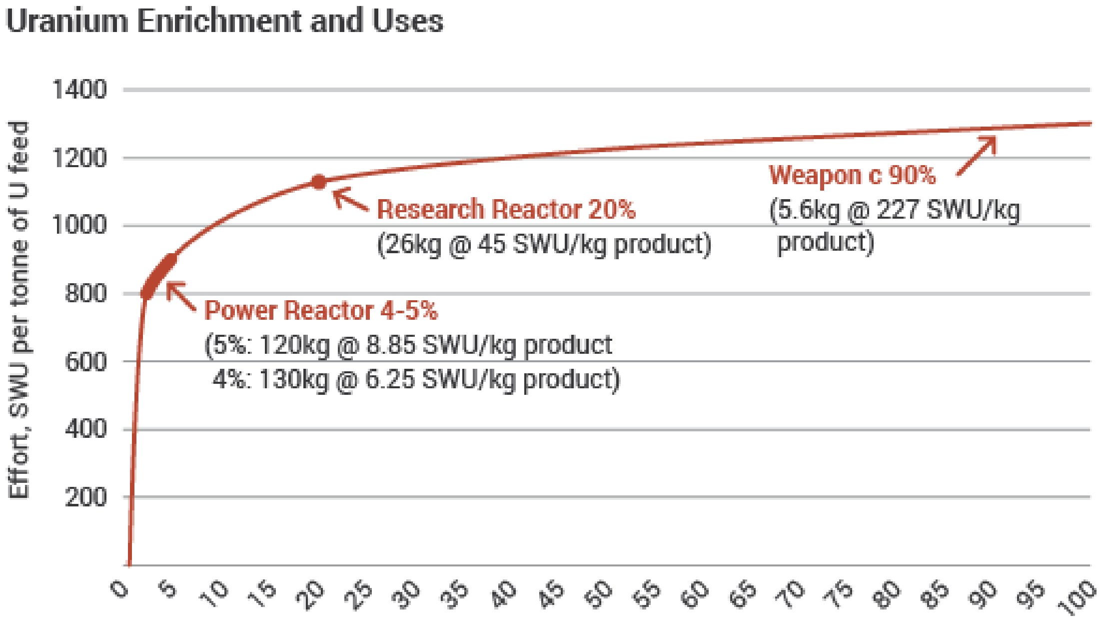


FIGURE 10

Separative Work Units Needed to Enrich Uranium to Power, Research, and Weapons grades

Source: https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/conversion-enrichment-and-fabrication/uranium-enrichment.aspx

There are several methods of enriching uranium. The most popular include:

1. Electro-magnetic Isotope Separation (EMIS)
2. Gaseous Diffusion
3. Gas Centrifuge
4. Separation of Isotopes by Laser Excitation (SILEX)

Method 1: Electro-magnetic Isotope Separation (EMIS)

One of the earliest enrichment techniques used in the Manhattan Project was electro-magnetic isotope separation (EMIS), which used large magnets to separate U^{235} from U^{238}. The first large-scale uranium enrichment facility, the Y-12 plant at Oak Ridge, Tennessee, used EMIS devices called Calutrons–named by their creator, Ernest Lawrence and his academic institution, the University of California at Berkeley (see Figures 11 and 12).

FIGURE 11
The Y-12 Plant at Oak Ridge, Tennessee
Source: http://www.lasg.org/sites/y12.htm

FIGURE 12
Alpha Track Calutron at the Y-12 Plant at Oak Ridge, Tennessee
Source: Ed Westcott/DOE

The EMIS process is based on the principle that a positively charged particle will follow a circular trajectory when passing through a uniform magnetic field. Two isotopes with the same kinetic energy and electrical charge, but with different masses (i.e., 235 U+ and 238 U+), will have different trajectories, with the heavier 238 U+ isotope having the larger diameter trajectory. The different diameters of the trajectories of the two uranium isotopes allow for the separation and collection of the material in different receivers or collector plates (see Figure 13).

FIGURE 13
Electric Magnetic Isotope Separation

EMIS is a batch process that can produce weapons-grade material from natural uranium. However, hundreds to thousands of units are required to produce large quantities of HEU because of the process's relatively low product collection rate. Also, getting large quantities of HEU requires a long time and many batch runs..

All five states recognized by the Nuclear Nonproliferation Treaty (NPT) as nuclear weapons states (the United States, Russia, the UK, France, and China) plus India, Israel, and Japan have tested or used the EMIS process for uranium enrichment. The EMIS process was abandoned by the United States during World War II in favor of gaseous diffusion because of the processes' high consumption of electricity, low conversion rate, and high construction costs. However,

EMIS was the principal process pursued by the Iraqi uranium enrichment program before it was destroyed in 1991.[3] The Iraqis adopted it because they could easily procure the magnet material without encountering technology transfer obstacles (EMIS technology is unclassified, see Figure 14).

FIGURE 14
EMIS "Calutron" Discovered in Iraq in 1991
Source: http://www.fas.org/nuke/guide/iraq/nuke/program.htm

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[3] Federation of American Scientists, "Iraqi Nuclear Weapons," available from http://fas.org/nuke/guide/iraq/nuke/program.htm.

Method 2: Gaseous Diffusion

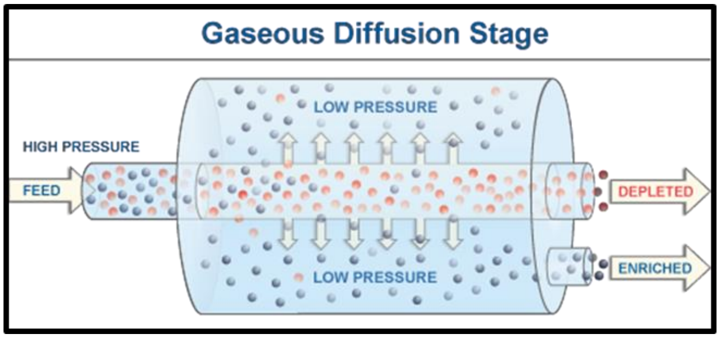

FIGURE 15
Gaseous Diffusion Stage

Lighter molecules in a gas will travel faster than their heavier counterparts. If the walls of a tube are semi- permeable, lighter isotopes of any given element will pass through the wall more frequently than heavier ones (see Figure 15).

Since an atom of U^{235} has three fewer neutrons than an atom of U^{238}, it is lighter. As a result, UF_6 molecules containing U^{235} will move faster and travel through the walls of a permeable tube faster than the molecules with U^{238}. With each successive stage of the gaseous diffusion process, the concentration of U^{235} becomes higher. The amount of separation during each stage is small, so it takes about a thousand stages to achieve LEU enrichment, i.e. to enrich natural uranium containing .7 of a percent U^{235} to low enriched uranium containing three to five percent U^{235}.

FIGURE 16
French Gaseous Diffusion Plants Located Behind the Two Nuclear Reactor Cooling Towers. Nuclear Reactors Are Needed to Power the Diffusion Plant.
http://www.eoearth.org/article/Uranium_enrichment

Like EMIS, gaseous diffusion plants require massive quantities of electricity to operate the plant's pumps. Their large size makes them expensive to build and to power (France's last operating gaseous diffusion enrichment plant required four nuclear power reactors with an electrical generating capacity of more than 3.6 gigawatts, see Figure 16). Nonetheless, gaseous diffusion plants can convert natural uranium to weapon-grade highly enriched uranium at a much higher rate than EMIS.

The first gaseous diffusion plant, the K-25 plant, was built at Oak Ridge, Tennessee during World War II as part of the Manhattan Project (see figure 17). Oak Ridge was chosen as the site for the gaseous diffusion plant because it was located in the middle of the Tennessee Valley Authority hydroelectric project, the only place in the United States that could provide enough electrical power to run the massive plant.[4]

The K-25 plant consisted of 50 four-story, U-shaped buildings measuring half a mile by 1,000 feet. It covered two million square feet, an area equal to 35 football fields, which is larger than the Pentagon. Inside, over 1,000 huge cells were linked in a series of cascades through which uranium hexafluoride gas traveled. The K-25 plant closed in 1987.

The large power requirements for these plants, along with their lengthy equilibrium time of nearly a year (the time needed from their startup to achieve a steady flow of UF6 at the desired high enrichment levels at the end of the cascades), makes it easier to detect an operating gaseous diffusion plants than other more efficient types of enrichment plants, like centrifuge enrichment systems.[5]

FIGURE 17
K-25 Plant – Oak Ridge, Tennessee

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[4] Ibid.

[5] Federation of American Scientists, “Centrifuges and Nuclear Weapon Proliferation,” available from https://fas.org/issues/nonproliferation-counterproliferation/nuclear-fuel-cycle/uranium-enrichment-gas-centrifuge-technology/centrifuges-nuclear-weapon-proliferation/

Method 3: Gas Centrifuge

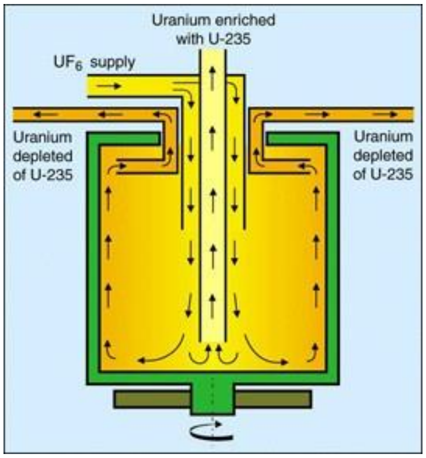


FIGURE 18
A Gas Centrifuge

A gas centrifuge is composed of a casing with a cylinder (or rotor) in its center that spins at high speed (see Figure 18 to the left and Figure 20 on the following page). As the rotor spins, the heavier isotopes of U^{238} are forced against the cylinder walls while the lighter atoms of U^{235} remain closer to the center. Also, the heavier uranium gravitates toward the bottom of the rotor.

Like gaseous diffusion, centrifuge enrichment uses gaseous uranium hexafluoride (UF_6) as feed. The UF_6 flows into the centrifuge from near the middle of the rotor. The enriched and depleted streams are removed from the centrifuge by separate pipes. Because one centrifuge cannot provide the amount of separation necessary to reach the required levels of enrichment for use in nuclear fuel or weapons, multiple banks of centrifuges must be connected together in a series of cascades (see Figure 19).

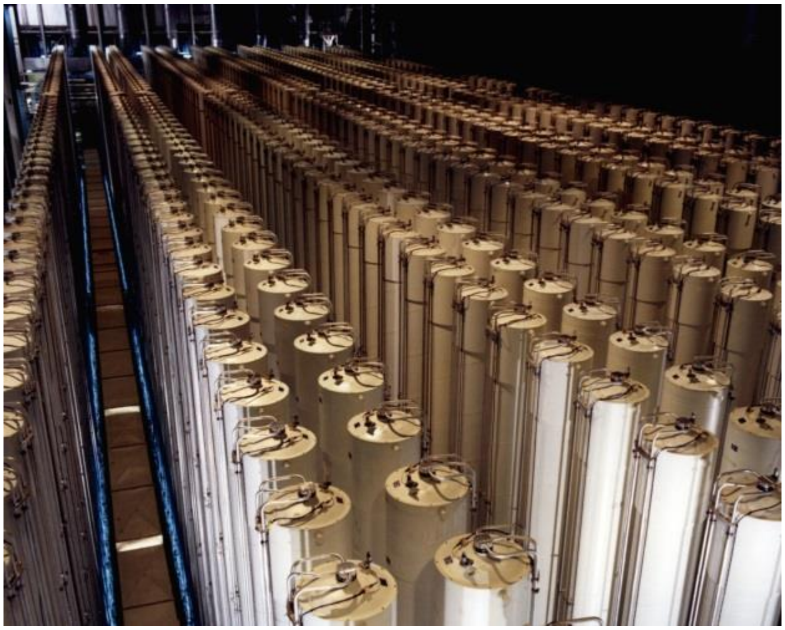


FIGURE 19
Gas Centrifuge Cascade

Centrifuges present a greater proliferation risk than gaseous diffusion plants. For any given level of enrichment, they have. A much smaller footprint than gaseous diffusion plants. Unlike diffusion plants, they can be deployed as modular units and be located in a number of relatively small buildings. Because they don't need large sites, they are easier to hide. Centrifuges are also far more energy efficient as other enrichment methods (they need only about five percent of energy that gaseous diffusion plants require), thus making it harder to detect on the basis of energy use.

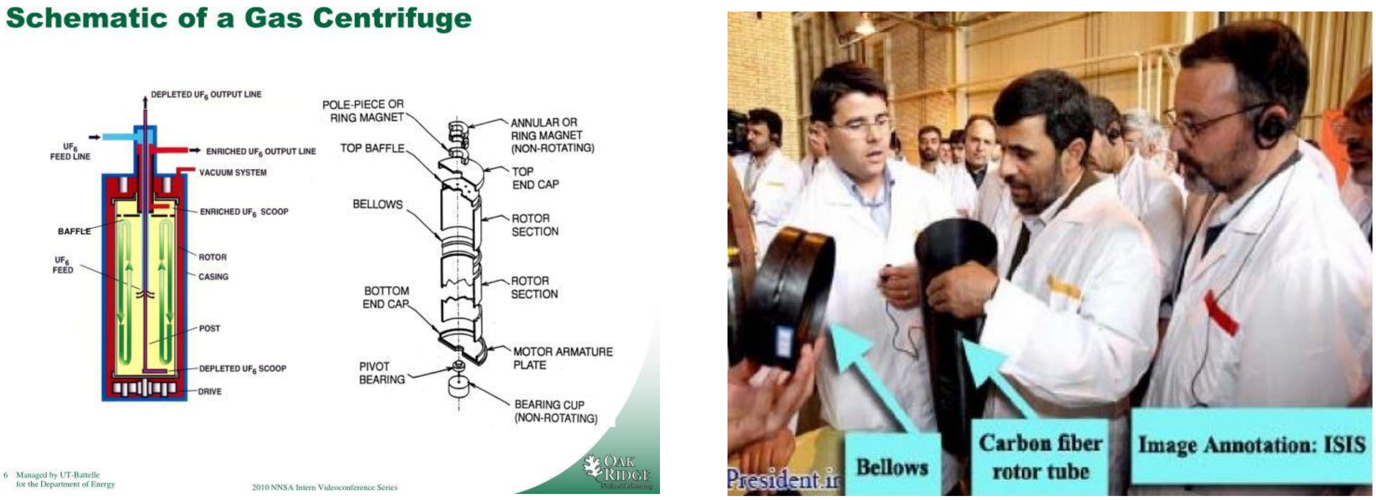


FIGURE 20
Gas Centrifuge Components

Finally, because the equilibrium time for a gas centrifuge cascade is measured in hours, not many months like gaseous diffusion plants, detecting diversions of material for weapons production in a timely manner (i.e., in enough time to prevent a bomb's worth of HEU from being produced).

Method 4: Laser Isotope Enrichment (AVLIS and SILEX)

Laser isotope enrichment is another, more advanced method used in uranium enrichment. Different isotopes of the same element absorb different colors, or frequencies, of light. As a result, a laser can be set to excite atoms of the desired isotope – such as U^{235}. When the laser hits the U^{235} atom, the atom's electrons become excited to a higher energy state. If enough energy is absorbed, an electron is ejected and the atom becomes positively charged. These positively charged atoms can then be deflected by an electrostatic field and drawn to electrically charged collector plates while the neutral U^{238} atoms pass through to be deposited as tailings in a collector. At least 20 countries have experimented with laser isotope enrichment technology.

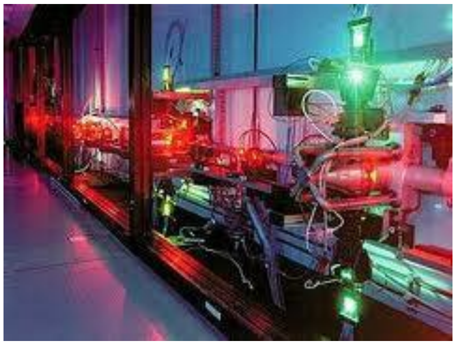
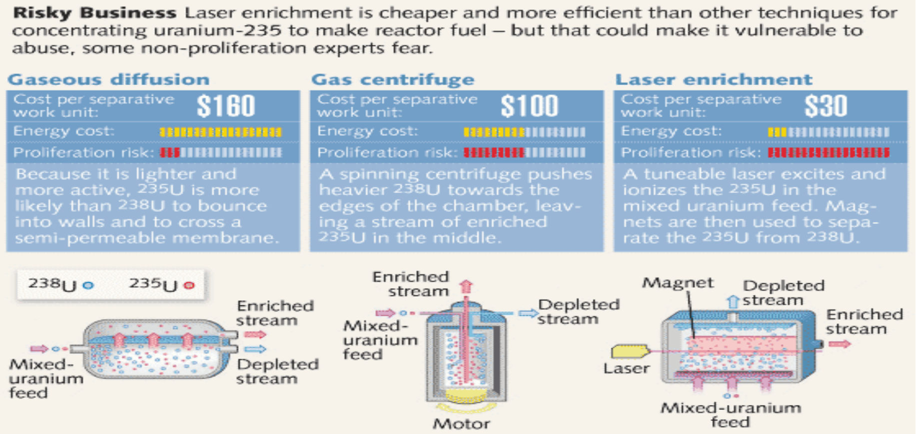


FIGURE 21
The AVLIS Process

FIGURE 22
The SILEX Process

The United States developed a system known as AVLIS (Advanced Vapor Laser Isotope Separation, see Figure 21), but it was not efficient enough to scale up for commercial use. A more recent joint effort with Australia's Separation of Isotopes by Laser Excitation, or SILEX (see Figure 22), was perfected for commercial enrichment by General Electric and Hitachi. SILEX, however, was not deployed for commercial use due to the surfeit of affordable enriched fuel supplied by existing centrifuge plants. SILEX is still under development and presents a proliferation risk. It can produce weapons-grade uranium in a small room, making it much harder to detect than the massive football field-sized gaseous diffusion plants or even smaller centrifuge systems (see Figure 23).[6]



Risky Business Laser enrichment is cheaper and more efficient than other techniques for concentrating uranium-235 to make reactor fuel – but that could make it vulnerable to abuse, some non-proliferation experts fear.

Gaseous diffusion
Cost per separative work unit: $160
Energy cost:
Proliferation risk:
Because it is lighter and more active, ^{235}U is more likely than ^{238}U to bounce into walls and to cross a semi-permeable membrane.

Gas centrifuge
Cost per separative work unit: $100
Energy cost:
Proliferation risk:
A spinning centrifuge pushes heavier ^{238}U towards the edges of the chamber, leaving a stream of enriched ^{235}U in the middle.

Laser enrichment
Cost per separative work unit: $30
Energy cost:
Proliferation risk:
A tuneable laser excites and ionizes the ^{235}U in the mixed uranium feed. Magnets are then used to separate the ^{235}U from ^{238}U.

FIGURE 23
Price and Price and Proliferation Risk Comparison of Diffusion, Centrifuge, and SILEX Enrichment

Source: Gail Overton, "Laser-based uranium enrichment plant sparks controversy," *Laser Focus World* July 5, 2012, available from http://www.laserfocusworld.com/articles/2012/07/laser-uranium-enrichment-plant-controversy.html

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[6] Jack Boureston & Charles D. Ferguson: "Laser Enrichment: Separation Anxiety," *Bulletin of Atomic Scientists*, March/April 2005, pp. 14-18, available from http://www.cfr.org/world/laser-enrichment-separation-anxiety/p7876.

Stage 4: Fuel Fabrication

FIGURE 24
Uranium Oxide Pellets

Following enrichmentUF_6 is transferred to a fuel fabrication facility as a solid. At the fabrication plant, the UF_6 is heated to a gaseous state. It then is chemically processed into uranium dioxide (UO_2), a black powder. This powder is compressed into small pellets and fired to create hard ceramic pellets (see Figure 24).

The individual pellets are then assembled in corrosion-resistant metal tubes. Once assembled, the product is referred to as a fuel rod, also known as a pin. The corrosion-resistant metal the tubes use is referred to as cladding. Cladding is made from various materials depending on the type of reactor they are used in. Zircaloy (zirconium alloy), stainless steel, and a special magnesium alloy called Magnox are the most common cladding materials (see Figure 25).

FIGURE 25
Zirconium Alloy Tubes
for Cladding

The finished fuel rods are grouped together into fuel bundles (also known as fuel assemblies) for use in the nuclear reactors (see Figure 26).

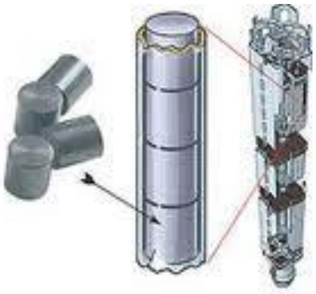

FIGURE 26
Left: Individual Fuel Pellets.
Center: Pellets Assembled into a Fuel Rod
Right: Fuel Rods Bundled Together in a Fuel Assembly

FIGURE 27
A Technician Arranges Fuel Pellets in a Trough Before Sliding the Cladding Over Them.

FIGURE 28
Completed Fuel Rods

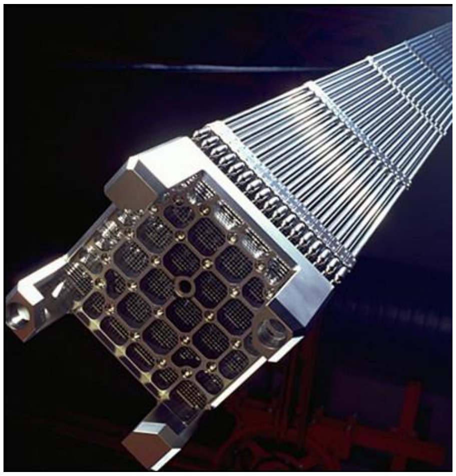

FIGURE 29
Fuel Rod Assembly

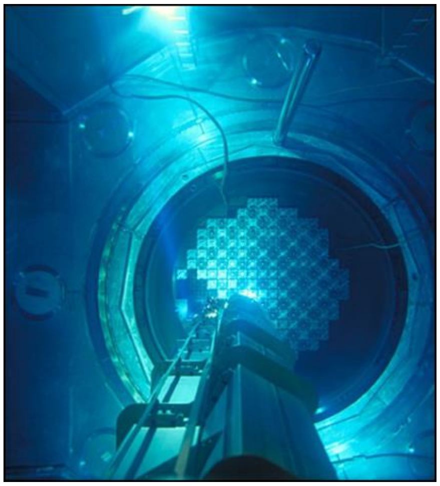

FIGURE 30
Fuel Assemblies in Reactor Core

Stage 5: Generating Electricity

Nuclear Energy Production

FIGURE 31
Interior of a Nuclear Containment Building During Refueling

Like power plants that burn coal or natural gas, nuclear reactors produce heat by boiling water into steam that can be used to spin turbines to generate electricity. However, instead of using fire to heat the water, nuclear reactors use the heat produced by nuclear fission.

The photo to the left (Figure 31) shows the interior of a nuclear containment building during a reactor refueling. In the center of the frame is the uncovered reactor core, located under 35 feet of water. On each side of the core are two steam generators. The steam from these generators is piped to the main electricity generating turbines in an adjacent building. The photo to the right (Figure 32) is a nuclear power station turbine hall. The turbines are enclosed in the red casings. After the steam spins the turbines, it is cooled in cooling towers (some of the water escapes and evaporates, producing the white cloud-like emissions from the tower). As it condenses back to water, it is reintroduced back to cool the reactor core. Figure 33 shows water vapor rising from the cooling towers of a nuclear power station.

FIGURE 32
Steam Turbines

Although, nuclear power plants are similar to other large electrical generating systems (e.g., gas, coal, hydro), there is two important differences.. All nuclear reactors produce radioactive materials and nuclear weapons-useable fuel, principally plutonium. This is true even of the most proliferation resistant reactor designs, the LWR.[7] Countries have historically used graphite, magnox, gas-cooled, RBMK, heavy water, and fast breeder reactors to make nuclear explosive plutonium. In many cases, these reactors also supplied electricity to the countries' power grid (. See the

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[7] For more on the proliferation risk of Light Water Reactors see Victor Gilinsky, Marvin Miller and Harmon Hubbard, "A Fresh Examination of the Proliferation Dangers of Light Water Reactors," Arlington, VA: Nonproliferation Policy Education Center, October 22, 2004, available from http://www.npolicy.org/article.php?aid=172.

chart on page 45 and Appendix 4 on pages 49-50 for additional information on reactors and plutonium production by reactor type).

FIGURE 33
Cooling Towers

All reactors have a core in which nuclear fuel–low or highly enriched uranium, natural uranium, plutonium or mixed uranium-plutonium–is modulated with control rods that produce a controlled fission reaction. Also, all reactors, except some gas cooled designs, have steam generators in which the hot coolant in the core transfers its heat to generate steam, which, in turn, is used to spin a turbine. The rotation of the turbine is used to spin a cluster of magnets to generate electrical voltage at a frequency that corresponds to the number of revolutions the turbine axle itself turns. Any steam used to turn the turbine is condensed back into water, which is then fed back into the reactor core to make sure it does not overheat. Any overheating may lead to a nuclear meltdown or other component failures. Finally, most, but not all, reactors place their reactor cores and steam generators within a reinforced concrete containment structure.

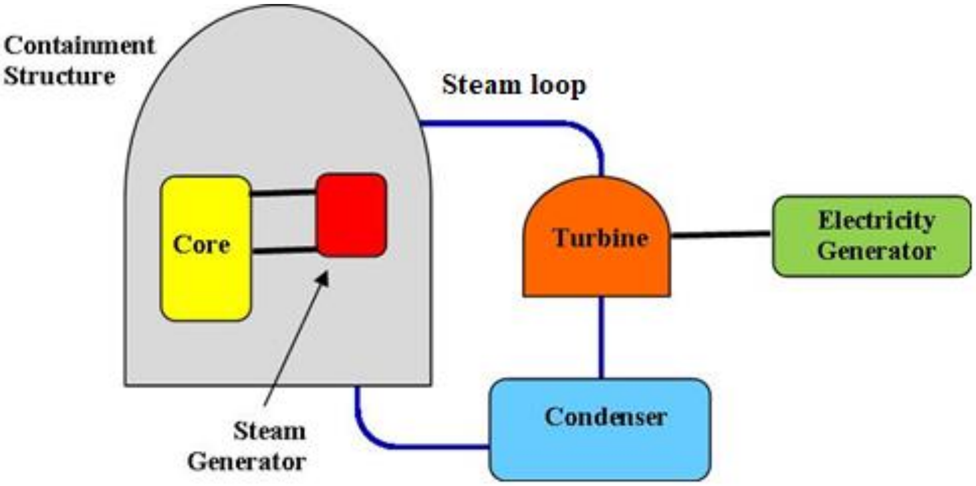

FIGURE 34
Simplified Schematic of Most Nuclear Reactors

Reactor Types

There are two basic types of reactors: Thermal reactors and fast reactors. Thermal reactors use relatively slow neutrons to fission nuclear fuel to make heat. Fast reactors rely on relatively high-energy, fast moving neutrons to fission nuclear fuel.

There are three popular kinds of thermal reactors: graphite-moderated reactors, heavy water, and light water reactors. The first kind of thermal reactor to be developed during the Manhattan

Project was graphite-moderated. It can be cooled with either gas or water and can be fueled with natural uranium. Another type of reactor that can use natural uranium for fuel is the heavy water reactor (HWR). Reactors that use natural uranium for fuel cannot use ordinary water (i.e. light water, H_2O) as a moderator because the light water molecules capture too many neutrons and so impede the nuclear chain reaction. To overcome this problem, natural uranium-fueled reactors use moderators such as heavy water and graphite, which do not impede the neutrons as much as common light water.

Again, light water reactors use common H_20 to moderate the neutrons and to cool the reactor. There are, in turn, two types of light water reactors: Boiling water reactors, which have one cooling loop, and pressurized water reactors, which have two. All light water reactors use low enriched uranium—uranium enriched between three and five percent in U^{235}.

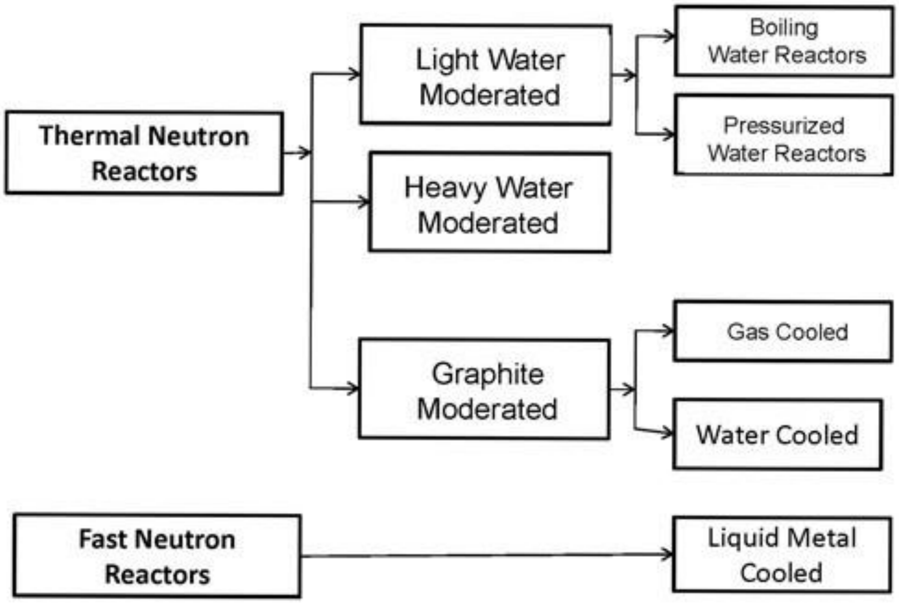

FIGURE 35
Types of Reactors

The second category of reactors is fast reactors that rely on fast neutrons to drive the reactors' fissioning process. These reactors are far more expensive to build and operate than thermal reactors and typically use plutonium or a mix of plutonium and uranium (mixed oxide or MOX) as fuel. They tend to also use molten salt (sodium) or lead, both metals, as coolants that do not slow or moderate the neutrons energy levels within the reactor.

Early Graphite Reactors

The first nuclear reactor was a graphite-moderated reactor known as the Chicago Pile-1 (CP-1, see Figure 36). The CP-1 was built as part of the top-secret Manhattan Project during World War II in an abandoned squash court under the old Alonzo Stagg Field at the University of Chicago. A critical mass of uranium pellets was inserted within layers of graphite blocks that moderated the speed of the neutrons. Cadmium control rods were used to control the nuclear chain reaction.

FIGURE 36
Chicago Pile-1
Source:
http://www.atomicarchive.com/History/sites/Metlab.shtml

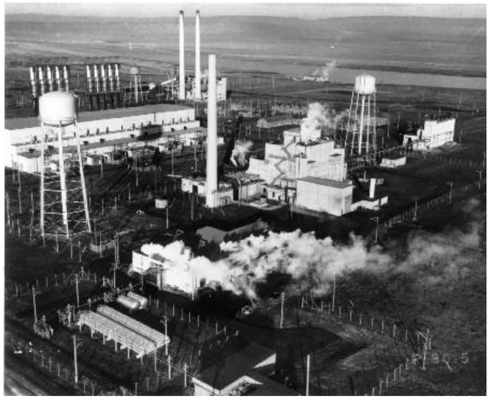

FIGURE 37
B Reactor
Source: http://www.b-reactor.org/nps/

Since it was designed for only small experimental demonstration purposes, the CP-1 did not use coolant or have any containment systems that subsequent, commercial reactors would.[8] Fuel could be loaded or unloaded while the reactor operated. This characteristic is called "on-line' or "on-load" fueling.

During the Manhattan Project, three large military production reactors were built at Hanford, Washington. They began operating in September 1944 and used metallic uranium as fuel, graphite as a moderator, and water from the Columbia River as coolant (see Figure 37).

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[8] For more information about CP-1 and the December 2, 1942, event, see Argonne National Laboratory, "The Chicago Pile 1 Pioneers," available from http://www.ne.anl.gov/About/cp1-pioneers/.

Magnox Reactor

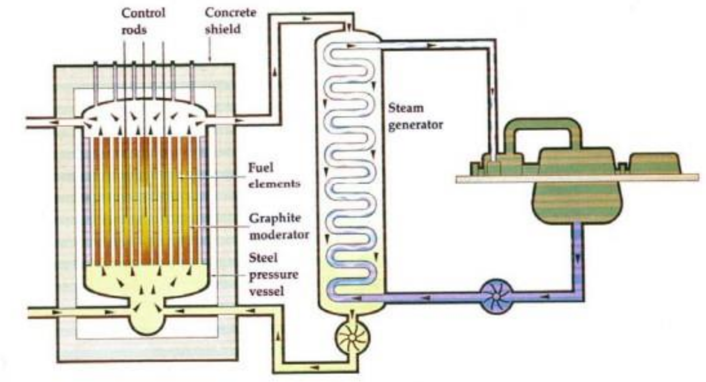

FIGURE 38
Magnox Reactor

Magnox technology, a more advanced form of a graphite-moderated reactor, was developed during the 1940s and 1950s in the UK. The first Magnox reactors were built in the UK at Calder Hall, which became the first power station to generate industrial levels of electricity from nuclear energy in 1956.[9] These plants were also used to make the UK's first plutonium bombs.

The fuel for Magnox reactors is natural uranium metal encased in magnox, a magnesium alloy. The fuel is placed in a graphite moderated core with compressed carbon dioxide (CO_2) gas that serves as the coolant. Heat generated by the fission in the core is carried away by the CO_2 to a steam generator, where the heat from the CO_2 boils water in a separate loop (to avoid contamination). The steam is then carried to the turbines which produce electricity.

Because Magnox reactors use natural uranium for fuel, they do not require enrichment facilities. Magnox reactors also are fueled on-line, i.e. they remain operational while spent fuel is replaced with fresh fuel. This precludes the ability to detect drops in electricity production that otherwise would serve as a signal that an unscheduled fuel exchange is occurring, possibly in order to divert weapons-usable material. It also allows the reactor operator to take fuel out when optimal levels of weapons-grade plutonium (Pu^{239} and Pu^{241}) are present. North Korea's first reactor, which it used to make plutonium for its first bombs, was a copy of the Magnox reactor the British used.

FIGURE 39
Wylfa MAGNOX Nuclear Plant, UK

Fuel	Natural Uranium
Moderator	Graphite
Coolant	Air
Refueling	On-line

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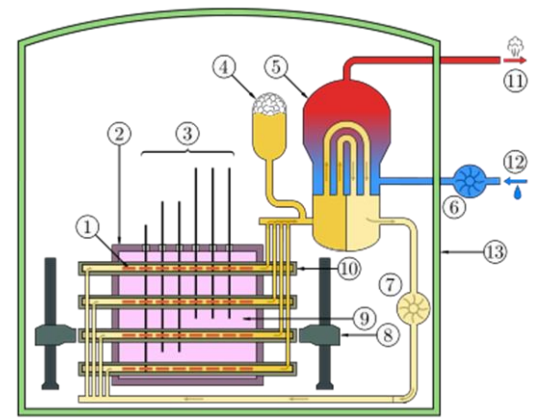
[9] World Nuclear Association, "Nuclear Development in the United Kingdom," available from https://www.world-nuclear.org/information-library/country-profiles/countries-t-z/appendices/nuclear-development-in-the-united-kingdom.aspx.

Heavy Water Reactors



The primary heavy-water loop is shown in yellow and orange. The secondary loop is in blue and red.

1. Fuel bundle
2. Calandria (reactor core)
3. Adjustor rods
4. Heavy water pressure reservoir
5. Steam generator
6. Light water pump
7. Heavy water pump
8. Fueling machines
9. Heavy water moderator
10. Pressure tube
11. Steam going to steam turbine
12. Cold water returning from turbine
13. Containment building of reinforced concrete

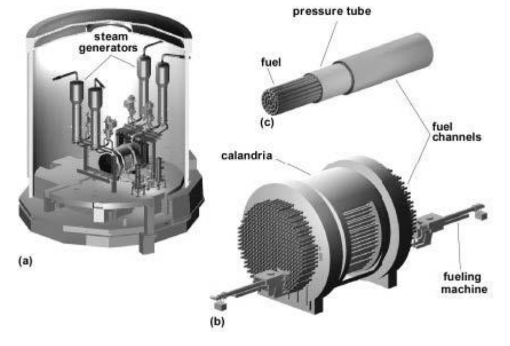


FIGURE 40
http://accessscience.com/loadBinary.aspx?filename=YB990650FG0010.gif

Heavy water reactors (HWRs) were first developed in Canada shortly after World War II. Canada started operating its first commercial heavy water power reactor in 1962.[10] HWRs operate in India, Argentina, Pakistan, Romania, Iran, Israel, China, and South Korea. Countries that used to have HWRs include Germany, France, Japan, Taiwan, Russia, Sweden, and the United States.

HWRs differ from LWRs in several ways. First, they use heavy water as a coolant and as a moderator. Since heavy water absorbs fewer neutrons than light water, it can facilitate a reactor achieving criticality with natural uranium instead of enriched fuel. Although heavy water production requires large plants that use electrolysis, a process that uses direct current (DC) to drive a chemical reaction, this process is far less complicated than isotopically enriching uranium, which LWRs require. Second, rather than containing the water and fuel assemblies in a pressure vessel, a HWR surrounds hundreds of "fuel tubes" with individual heavy-water coolant "pressure tubes."

Fuel	Natural Uranium clad in zircaloy
Moderator	Heavy Water
Coolant	Heavy Water
Refueling	On-load

This heavy water coolant is kept pressurized as a liquid and is used to heat water in a separate boiler that helps generate steam. A separate system of heavy water–surrounding the pressure tubes–acts as the

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[10] World Nuclear Association, "Nuclear Power in Canada," available from https://www.world-nuclear.org/information-library/country-profiles/countries-a-f/canada-nuclear-power.aspx.

reactor's primary moderator. This moderator is kept at room temperature and approximately normal pressure.

FIGURE 41
IR-40 Heavy Water Reactor Near Arak, Iran

Heavy Water Production

FIGURE 42
The Arak Heavy Water Project Located 120 Miles Southwest of Tehran

Heavy water is the name for water molecules in which the hydrogen atoms are deuterium, a hydrogen isotope that consists of a proton and a neutron. The two extra neutrons in the deuterium (D^2) in heavy water molecules make them heavier than molecules of common "light" water or H_2O. Heavy water (D_2O) is naturally present in normal water, but in tiny amounts (see Figures 43-44). The separation process for heavy water is similar to that used to distill alcohol or produce ammonia. Large processing towers like those pictured above (Figure 42) are used along with equipment common to other chemical and petroleum industries. Few of these items, however, are available "off-the-shelf." Also, the equipment must be tailored for making heavy water. Heavy water does not have much use beyond its role as moderator in certain nuclear reactors, but its production is monitored and its export is internationally controlled. The presence of heavy water production plants can be an indication of a state's intent to develop nuclear weapons.

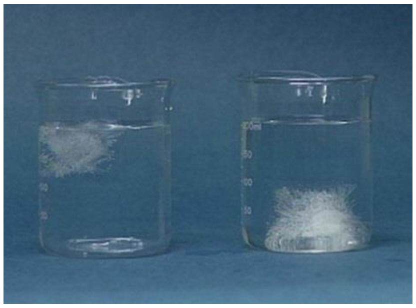

FIGURE 43
Frozen D_2O (At Right) Sinks in Light Water While Frozen H_2O Floats.

Heavy water is produced in Norway (where the first production plant was built), Canada, India, Iran, and Argentina. The United States no longer operates any nuclear reactors that require heavy water.

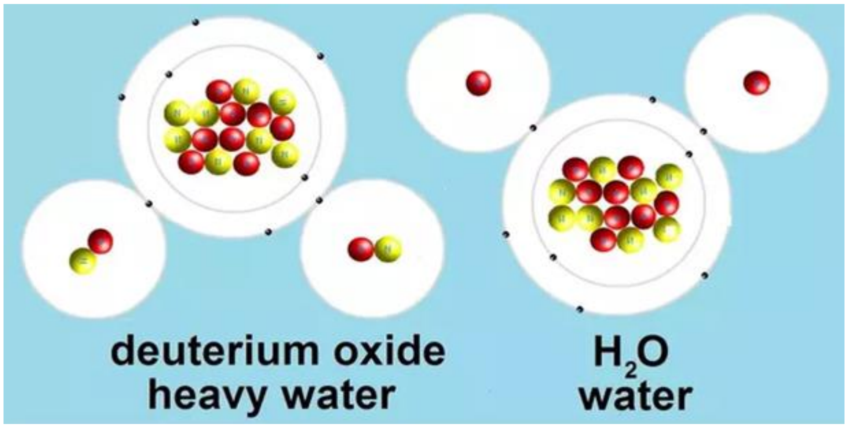

FIGURE 44
D_2O and H_2O Atomic Structure

Liquid Metal Fast Breeder Reactor (LMFBR)

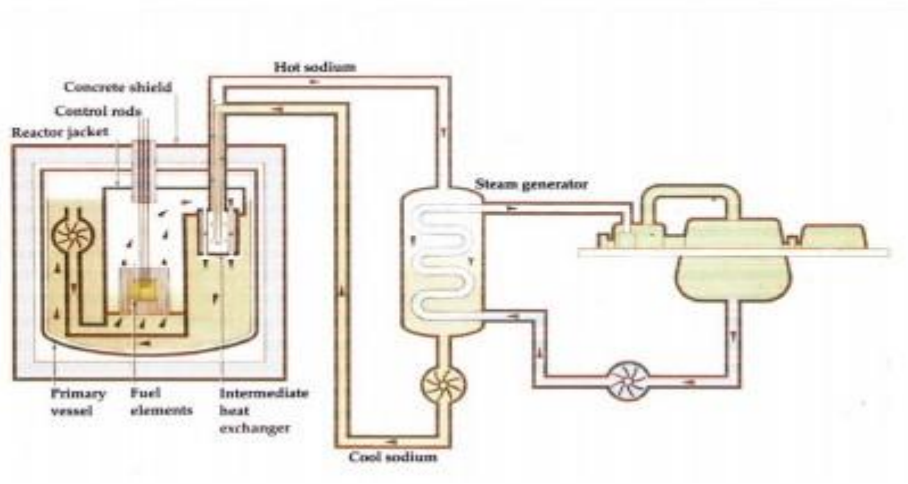

FIGURE 45
Sodium-Cooled Fast Reactor

Development of fast breeder reactors began in the United States in 1951. The UK started a separate program in the late 1950s, and by the 1970s there were breeder programs underway in the USSR, France, Japan, and Germany. India's program got underway in the mid-1980s. Its first large fast reactor is expected to come on line soon, which will be used to make both power and weapons plutonium. Today, only Russia and China have operating fast breeder reactors.

Fuel	Pu or MOX – clad in stainless steel
Moderator	None
Coolant	sodium, lead
Refueling	Off-load

The LMFBR is designed to be fueled with plutonium based-fuels. It has no moderator to slow neutrons down, which differentiates it from thermal reactors. The fissioning of plutonium caused by the fast neutrons releases a relatively large number of neutrons in turn. By surrounding the plutonium with blankets of fertile U^{238} (or thorium), neutrons not used in the chain reaction are absorbed, which creates new plutonium or U^{233} at a rate faster than existing fissile material is consumed. Fast reactors require coolants that do not slow the fast neutrons down in order to function. Sodium is a popular primary loop coolant for this purpose, as is lead. Since liquid sodium tends to react violently with water (or any compound that contains oxygen), even the slightest of leaks in the plant's heat exchangers can cause serious problems (historically LMFBRs have had trouble operating due to heat exchanger leaks). An example of a LMFBR is the Phénix, located in France. France used LMFBRs as military production reactors.[11] India is planning to do so as well (see Figures 46 and 47 below). Breeders in France, the UK, Germany, the United States, and Japan have either been shuttered due to technical problems or have not been opened for operation.

FIGURE 46
India's Prototype Fast Breeder Reactor Under Construction at Kalpakkam

FIGURE 47
Phénix, Prototype Fast Breeder Reactor Marcoule, France – Shut Down 2009

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[11] Mycle Schneider, "Fast Breeder Reactors in France," in *Fast Breeder Reactor Programs: History and Status, International Panel on Fissile Materials*, 2010, p. 26, available at http://fissilematerials.org/library/rr08.pdf and M. V. Ramana, "India and Fast Breeder Reactors," in Ibid. pp. 45-46.

Light-Water Reactor (PWR)

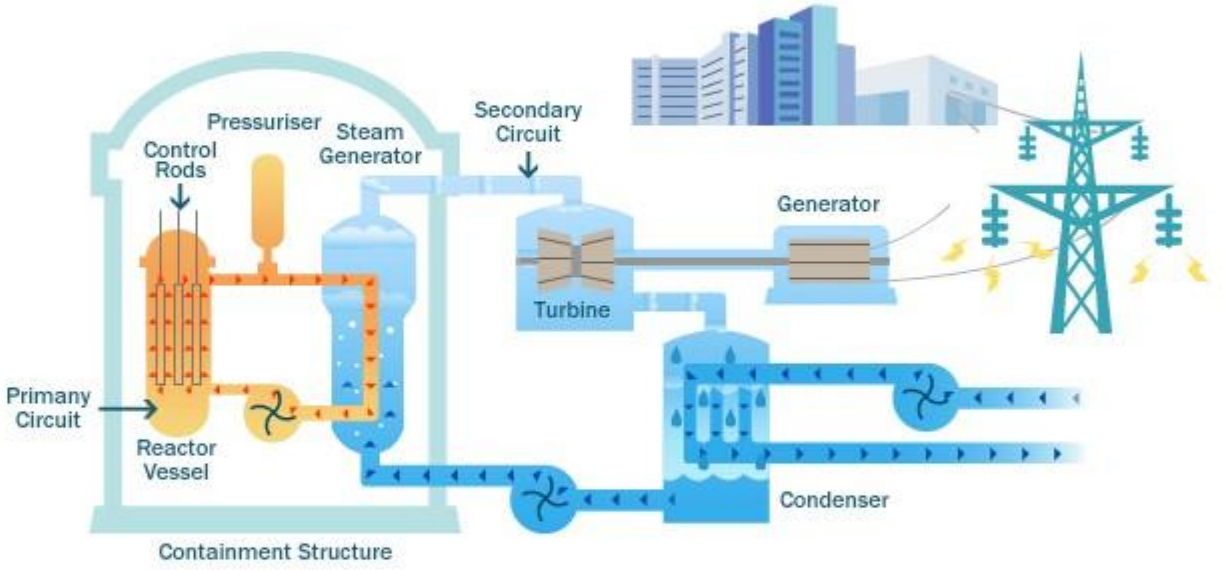

FIGURE 48
Typical Pressurized-Water Reactor
https://www.clpgroup.com/NuclearEnergy/Eng/images/power/4_1_2a.jpg

The early graphite reactor design was built during World War II for the Manhattan Project was selected in part because it could use natural uranium for fuel (the graphite slowed, but did not absorb the neutrons released by the uranium). Enrichment technology was still in its early stages, so enriched uranium was both expensive and in short supply. After the war, when enriched uranium became more available, new reactor designs that used enriched uranium and light water as a moderator and coolant were developed. The U.S. Navy developed the first version of a light water reactor (a pressurized water reactor, or PWR) in the early 1950s for the first nuclear submarine, the USS Nautilus.[12]

In a pressurized water reactor, the steam is cooled and condensed, then pumped back to the reactor core. The reactor coolant (primary loop) and turbine steam (secondary loop) are both water, but the water supplies in each loop are keep separated to prevent radiation contamination.

Fuel	LEU clad in zircaloy
Moderator	Light Water
Coolant	Light Water
Refueling	Off-load

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[12] More about the USS Nautilus can be found here: Attila Nagy, "The World's First Nuclear Submarine Was Launched 60 Years Ago," *Gizmodo*, January 21, 2014, available from http://gizmodo.com/the-worlds-first-nuclear-submarine-was-launched60-yea-1505899173.

FIGURE 49

Three Mile Island Nuclear Power Plant, U.S.

Light-Water Reactor (BWR)

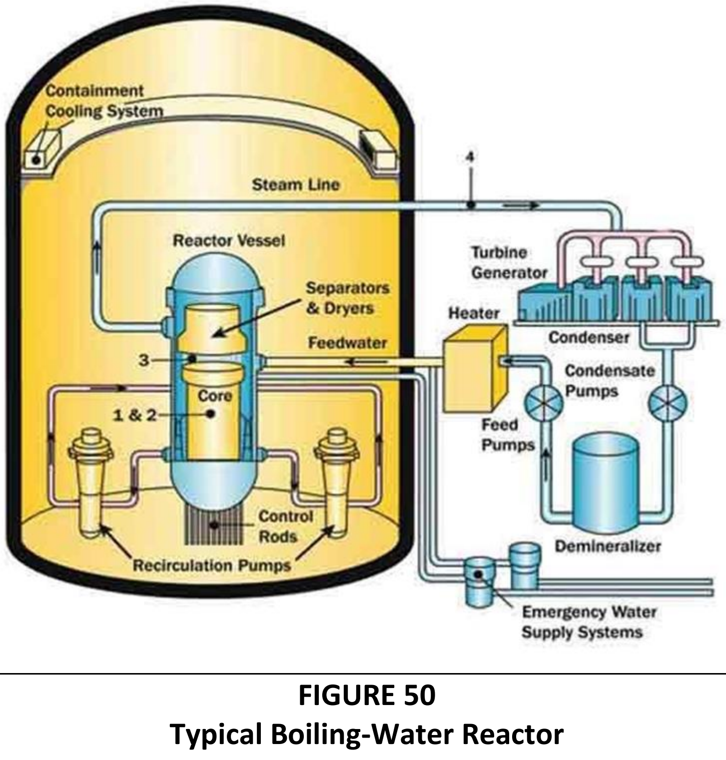

FIGURE 50

Typical Boiling-Water Reactor

www.nrc.gov/reactors/bwrs.html

The boiling water reactor (BWR), a variant of the light water reactor, was developed by the Idaho National Lab and General Electric in the mid-1950s. In a boiling water reactor, the steam is cooled and condensed, then pumped back to the reactor pressure vessel. Water used as a coolant and modulator in the BWR core is the same water boiled into steam to spin the turbines. There is no secondary coolant loop.

RBMK

The Soviet-designed RBMK (Reactor Bolshoy Moshchnosty Kanalny—high-power channel reactor) is a pressurized water-cooled reactor with a graphite moderator. It was developed in the 1950s for military plutonium and power production. The design is now considered obsolete, but there are still several RBMKs operating in Russia.[13]

Fuel	LEU
Moderator	Light Water
Coolant	Light Water
Refueling	Off-load

FIGURE 51
Fukushima Daiichi BWR Nuclear Power Plant, Japan

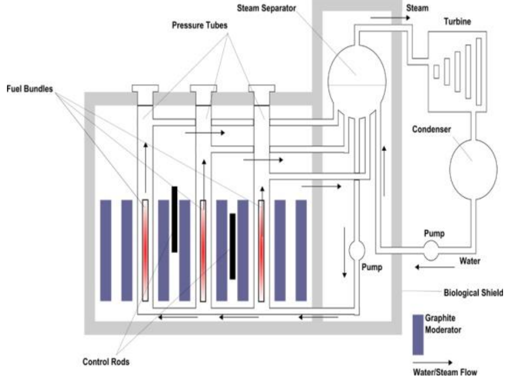

FIGURE 52
RBMK (Reactor Bolshoy Moshchnosty Kanalny)
http://www.world-nuclear.org/info/inf31.html

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[13] World Nuclear Association, "RBMK Reactors," available from https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/appendices/rbmk-reactors.aspx

The RBMK uses fuel rods formed of pellets of slightly-enriched uranium oxide enclosed in zircaloy tubes. The coolant is pressurized before being passed through the fuel rod assemblies, which have individual channels. The plant has no containment building. Unlike light water reactors, whose reactivity declines with a loss of coolant, RBMKs' reactivity will increase. The accident at Chernobyl was caused by the loss of coolant induced by a lack of sufficient emergency power to run the reactor's coolant pumps.

Fuel	LEU clad in zircaloy
Moderator	Graphite
Coolant	Light Water
Refueling	On-line

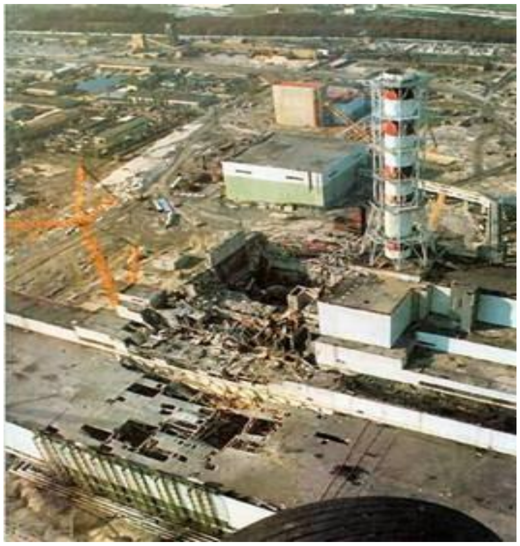

FIGURE 53
Chernobyl Nuclear Power Plant, Ukraine

High Temperature Gas Cooled Reactor

The high temperature gas-cooled reactor (HTGR) is yet another variation of the graphite moderated reactor. The design for the HTGR was proposed by American scientists in 1947 and developed during the 1950s. While the moderator and coolant of the high temperature gas-cooled reactor (HTGR) are much the same as in the Magnox reactor, the fuel and operation are quite different. Higher operating temperatures, as well as the use of helium rather than carbon dioxide as the coolant gas afford higher thermal efficiencies. The high temperatures are possible since the flow rate of gas coolant is so high that it can remove more heat from the core than with liquid coolants. HTGRs are able to use a wide variety of fuels: HEU, LEU, or thorium (see figure 55).

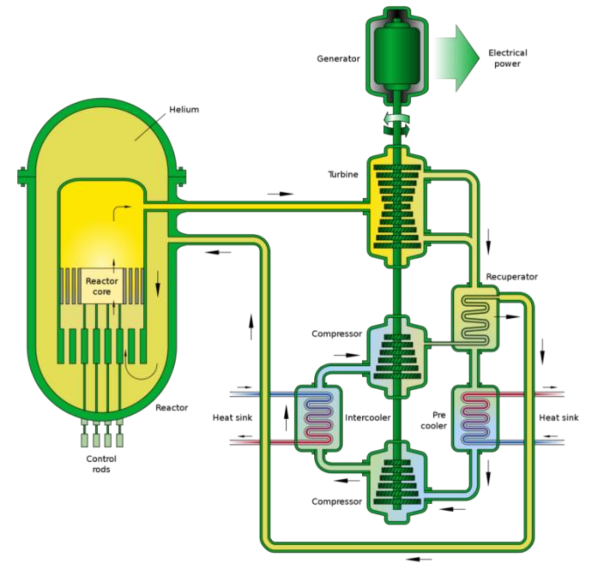

FIGURE 54
High Temperature Gas-Cooled Reactor (HTGR)
https://en.wikipedia.org/wiki/Gas-cooled_fast_reactor

In 1966, the experimental Peach Bottom 1 reactor in the United States became the first HTGR to produce electricity. A second HTGR was built at St. Vrain (see Figure 56 below). Both are now closed.

FIGURE 55
Fort St. Vrain HTGR Power Station. It Operated from 1976 to 1989.
http://www.fsvfolks.org/FSVHistory_2.html

Fuel	Uranium clad in a graphite matrix
Moderator	Graphite
Coolant	Helium
Refueling	Off-load

Summary of Reactor Characteristics by Type

Type of	Magnox Reactor	Heavy Water Reactor (CANDU)	Liquid Metal Fast Breeder Reactor (LMFBR)	Pressurized Water Reactor (PWR)	Boiling Water Reactor (BWR)	High Temperature Gas-Cooled Reactor (HTGR)
Name of Example	Chapelcross (UK)	Pickering (Canada)	Phenix (France)	Zion (USA)	Browne Ferry 2 (USA)	Fort St. Vrain (USA)
Heat Output	840 MWt	1744 MWt	563 MWt	3250 MWt	3293 MWt	842 MWt
Electrical Output	275 MWe	308 MWe	233 MWe	1050 MWe	1065 MWe	330 MWe
Fuel	Natural Uranium Metal clad in Magnox alloy	Natural uranium oxide clad in zircaloy	Mixed uranium and plutonium oxide (MOX), 20 -27% enrichment, clad in stainless steel	Uranium oxide, 3% enriched, clad in Zirconium	Uranium oxide, 2.2% enriched , clad in zircaloy	Uranium carbide particles, enriched, coated in graphite matrix
Moderator	Graphite	Heavy Water	None	Light water	Light water	Graphite
Coolant	Carbon dioxide	Heavy water	Liquid sodium	Light water	Light water	Helium
Refueling	On-load	On-load	Off-load	Off-load	Off-load	Off-load

An Additional Word on Off-line or Off-load and On-line or On-load Refueling

FIGURE 56
LWR Refueling

In order to refuel LWRs and breeder reactors, the reactor must be shut down (i.e. taken off-line) and the reactor pressure vessel unbolted and raised to get at the reactor core (see Figure 57 above). This type of off-line refueling is also referred to as off-load. The drop in energy production can be detected by monitoring satellites—either visually looking at cooling tower plumes or infrared heat signatures from containment buildings. Frequent or unscheduled reactor shutdowns can be a sign that a state is removing irradiated fuel early when the plutonium 239 level is optimal for weapons use rather than the 12-18 months that provides maximum power from the fuel.

On-line Refueling—HWRs and GCRs

In contrast, the HWR,RMBK and GCR cores, which are not contained in a pressure vessel, can be continuously refueled while operating (i.e. while on-line). On-line or on-load refueling poses significant proliferation challenges. First, there is no corresponding drop in energy production when the reactor is being refueled. This makes it easier to divert spent fuel secretly for weapons production. Second, on-line fueling makes it easier for the operator to control how long the fuel is irradiated—i.e., to control how high the percentage of odd isotopes of the plutonium produced might be.

Plutonium Production by Reactor Type

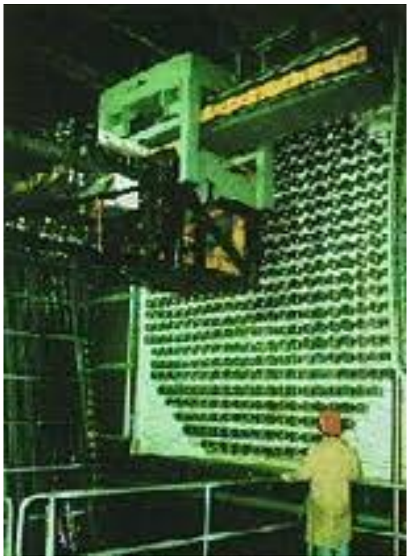

FIGURE 57
CANDU Reactor
This photo shows the refueling machine. New fuel assemblies are added horizontally and the spent fuel assemblies are pushed out to the spent fuel storage area.

Plutonium is naturally created as a by-product of the fission reaction taking place in the core of all nuclear reactors. The U^{238} in natural uranium absorbs neutrons released by the U^{235} atoms and produces Pu^{239}, which, like U^{235}, is capable of fission. However, the production of other plutonium isotopes (e.g. Pu^{240} and Pu^{241}) happens more slowly than that of Pu^{239}, so fuel that has only been in the reactor a short time has a greater fraction of Pu^{239} than it does Pu^{240}, Pu^{241}, and Pu^{242}. The fuel rods can be removed from the reactor early—before they are fully "spent"—in order to yield the maximum fraction of Pu^{239}. The plutonium can then be separated from the rest of the spent fuel through a series of steps known as reprocessing. Since all plutonium can be used as fuel in nuclear weapons, the operation of any nuclear reactor automatically presents a proliferation risk.[14]

Fissile Material Produced by a 1,000 MWe Reactor Operating at 70% Load Factor for One Year

Reactor Type	**Initial Fuel (Enrichment)**	**Produced Pu (kg)**
Light-Water Reactor	U^{235} (3%)	175*
High Temperature Gas-Cooled Reactor	U^{235} (93%)	29 (plus 64kg U^{235})
Canadian Deuterium-Uranium (CANDU)	U (natural)	360
Fast Breeder Reactor	MOX	300

** For a LWR that has been operating for over 36 months.*

Note that low-enriched reactors produce more plutonium than high enriched reactors (the fast breeder reactor uses plutonium as fuel, so much of what is produced will actually be reused as fuel). Again, production in a CANDU is the highest for a given power generation.

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[14] Charles D. Ferguson, "Proliferation Risks of Nuclear Power Programs," *Nuclear Threat Initiative*, December 1, 2007, available from http://www.nti.org/analysis/articles/risks-nuclear-power-programs/.

Historically, the line between the production of nuclear power and the manufacture of nuclear weapons has been crossed more than once. For example:

- The United States, Russia/USSR, UK, India, DPRK, and France have all made weapons using plutonium that had been generated by reactors connected to their electrical grids.
- The United States tested power reactor-grade plutonium in an early 1960s weapons design.
- India claims it tested a power reactor-grade plutonium device in 1998.
- The Turks did research to demonstrate that plutonium from LWRs could be used to make bombs.
- LWRs in the United States are currently used to produce weapons-grade tritium (another reactor by-product).

Stage 6: Spent Fuel Management

Direct Disposal vs. Reprocessing

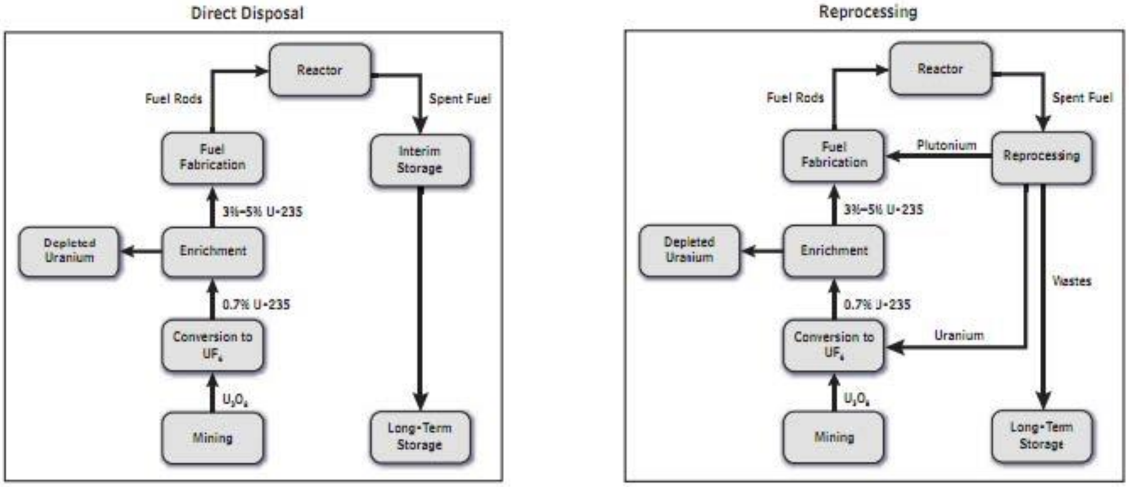


FIGURE 58
Direct Disposal vs. Reprocessing

Once the fuel in a reactor has used so much of the fertile U^{235} atoms that fission is no longer sustainable (the amount of irradiation is known as burn-up), the fuel must be removed. The nuclear fuel cycle can follow one of two tracks.

With the once-through or direct disposal cycle, the spent fuel is removed from the reactor and stored without recovering the plutonium or remaining uranium. In contrast, a closed fuel cycle involves recycling or reprocessing of the spent reactor fuel to chemically extract the plutonium and unused uranium so that they can be reused. Plutonium is combined with natural uranium to form a new type of fuel known as MOX—mixed oxide fuel—that can be used in fast breeder reactors and modified light water reactors. About one percent of used or spent fuel is plutonium.

While reprocessing increases energy production from a given amount of uranium, it is extremely costly in comparison to the once-through fuel cycle. There are also significant proliferation risks associated with reprocessing. The plutonium removed from spent fuel is a direct-use material that can be diverted for weapons. The United States stopped reprocessing fuel in the 1970s, but other countries–like France, China, Russia, and India—currently–operate reprocessing facilities.

Reprocessing

France and India reprocess on a commercial scale; China, Japan and South Korea are planning to do so. The United States, UK, Iran, Russia, Pakistan, China, and Israel all have or had produced nuclear weapons by reprocessing spent fuel from military production reactors. Commercial reprocessing programs in the United States, UK, and Germany, however, have been terminated.

Commercial reprocessing plants are large and expensive, costing many billions to build and even more to operate. The almost completed plant in Japan at Rokkasho will cost more than $20 billion to complete and over $100 billion to operate over its lifetime (see Figure 60). These plants can take more than a decade to build and can produce hundreds of tons of plutonium, equivalent to more than a 1,000 bombs' worth of plutonium a year.

FIGURE 59
Rokkasho, Japan: Large and Expensive
Source: http:www.japanfocus.org/-Shimbun-Asahi/2120

A covert reprocessing plant, however, can be made quickly and quite small for very little. In the 1950s, the United States designed reactors that had reprocessing lines small enough that they could be fitted within the reactor's containment structure. But they were never built. Israel actually operates a relatively small reprocessing plant within the same building as its reactor at Dimona. In the 1970s, after the Indian test explosion, Congress focused on the dangers of allowing "peaceful" reprocessing of the sort India engaged in. The nuclear industry dismissed their worries arguing that it was so easy to reprocess covertly that there was no point in trying to limit overt commercial reprocessing. To prove their point, the nuclear industry made public a cheap and small reprocessing plant design that could be built in six months. This reprocessing plant design could produce a bomb's worth of plutonium a day in a space smaller than most warehouses (see Figure 61 below). This plant could not be detected until it began operating and if it was built with a structure designed to filter and contain Xeon emissions, its operation might not be detected at all.

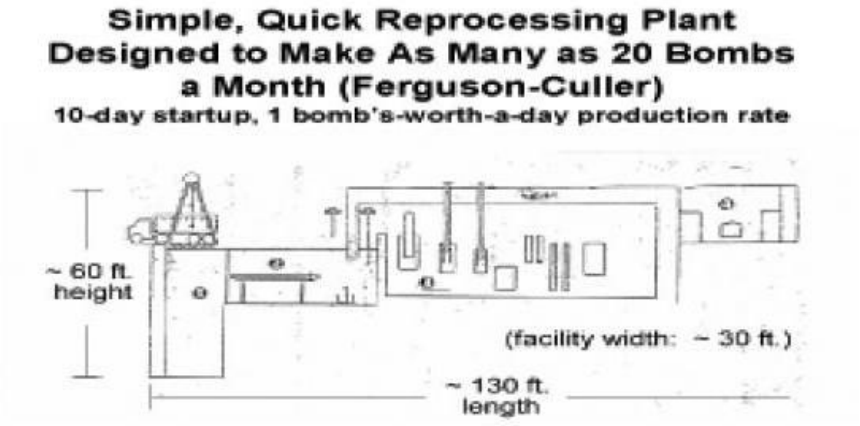


FIGURE 60
Ferguson Culler Design: Small and Cheap

Reprocessing Steps

There are 5 main steps to reprocessing:

1. **Cooling**
2. **Head-end treatment**
3. **Separation/extraction**
4. **Conversion of plutonium nitrate to plutonium oxide**
5. **Storage of radioactive wastes**

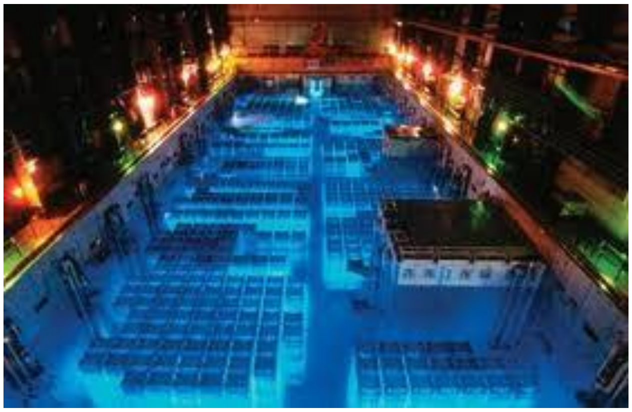


FIGURE 61
Cooling Pool

Cooling: The cooling phase involves reducing the temperature and the radioactivity of the spent fuel. In commercial reprocessing efforts, this is accomplished by placing the spent fuel in wet storage cooling ponds for several years (see Figure 62). In a weapons production effort, the cooling period can be far shorter.

Head-end treatment: Once cooling has been accomplished, the next step is to remove the spent fuel from its cladding and dissolve it. There are a wide variety of cladding materials, depending on the type of fuel and the coolant used in the reactor. Thus, a single reprocessing facility may not be able to handle all types of fuels without modification.

The fuel rods in a large military effort are handled remotely inside concrete “caves,” which are several meters thick and have special radiation-absorbing windows. The remote manipulators can then be used to perform one or more of the de-cladding processes. Uranium oxide fuel rods are mechanically chopped into sections then dropped into acid which dissolves the fuel but not the cladding “hulls” (see Figure 63). The solution is then clarified in centrifuges and passed to the next step.

FIGURE 62
Head-end Process

Separation/Extraction: Once the fuel has been dissolved and clarified, it can then undergo the third major step: chemical extraction and separation of the uranium and plutonium from the fission by-products. The only separation method in wide commercial use today is the PUREX

(Plutonium Uranium Extraction Plant) process. There are basically three steps in the process: 1) extraction of the uranium and plutonium from the fission products; 2) partitioning the uranium from the plutonium; and 3) stripping either the uranium or plutonium from its accompanying organic solvent.

The fundamental principle of the PUREX process is that uranium and plutonium are chemically different than the other fission products in the spent fuel. When mixed with aqueous nitric acid and an organic solution of tributyl phosphate (TBP) and kerosene, the uranium and the plutonium attract to the organic solution while the other fission products tend to adhere to the aqueous solution (See Figure 63 below):

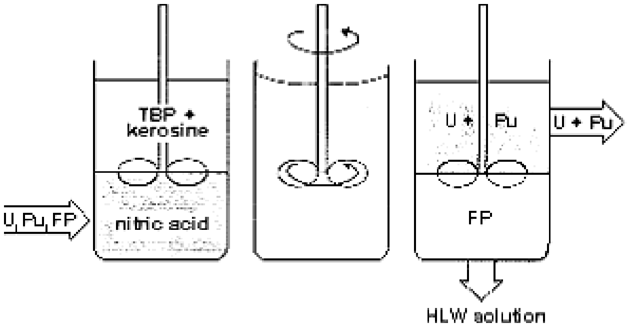


FIGURE 63
PUREX – Extraction Process

A tall column (20 stories at the British Windscale, see Figure 64 below) is employed to pulse several solutions: A heavy aqueous nitric acid solution, which is introduced at the top of the tower; the dissolved spent fuel, which is injected in the tower's middle; and a lighter organic tributyl (TBP) phosphate solvent, which is introduced at the tower's bottom. Gravity alone, an impulse piston, or a series of mixer-settler banks may then be used to bring the liquids into contact. The plutonium and uranium are absorbed by the aqueous solution and the other spent fuel products are absorbed by the organic TBP-kerosene solution.

FIGURE 64
Windscale Reprocessing Towers

A second extraction step is then taken to extract the plutonium from the uranium. The uranium and plutonium mixture, which is still suspended in an aqueous solution of nitric acid, is again immersed into a fresh stage of organic solvent and nitric acid with a reducing agent. As the dense nitric acid passes down through the organic solution, the reducing agent converts the plutonium to a non-soluble form that sinks while the uranium moves upward in the organic solvent. Both, then, are extracted or stripped from the aqueous and organic solutions they reside in and passed to a uranium-stripping step while the plutonium leaves from the bottom for an additional extraction and stripping sequence (see Figure 66). The plutonium is then converted to plutonium oxide.

FIGURE 65
Plutonium Uranium Extraction Plant at Hanford, Washington
http://www.hanford.gov/page.cfm/PUREX

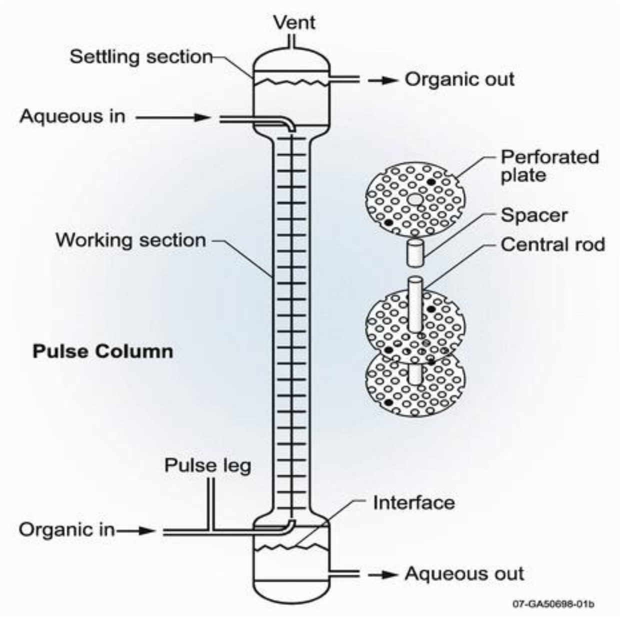


FIGURE 66
Reprocessing Pulse Column

Storage of Fuel and Other Waste

There are also various techniques for storing spent nuclear fuel and other waste. Short term storage methods range from placement of spent fuel assemblies in pools to cool before reprocessing or permanent storage in dry casks, storage in containers on the ground of nuclear power facilities before removal, or to permanent storage facilities underground.

Most spent nuclear fuel is stored in pools located at the reactor sites. When pool capacity is reached, the cooled fuel can be removed to above-ground dry storage casks made of steel and heavily reinforced concrete.

Spent Fuel Storage

Spent fuel is generally kept in storage pools (see Figure 67) for several years. This guarantees the temperature and radioactivity have reduced to manageable levels before it is removed to dry casks. Dry storage is becoming increasingly popular since it frees up room in the pools for additional fuel storage. The dry casks can then be stored on-site at the reactor. The casks can be stored either horizontally or vertically, typically on concrete pads to protect from leaks (see Figure 68).

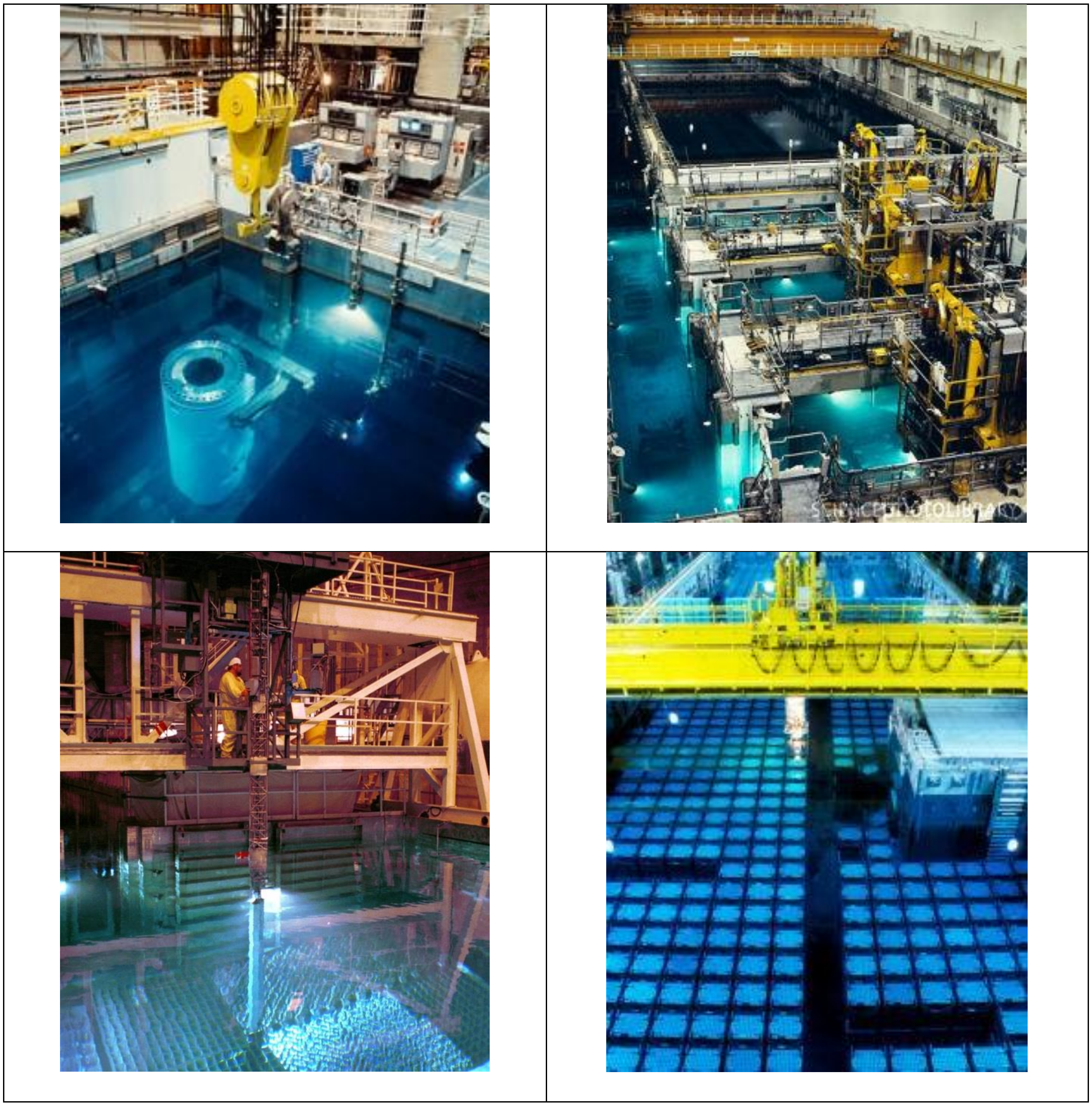


FIGURE 67

Cooling Pools for Spent Fuel

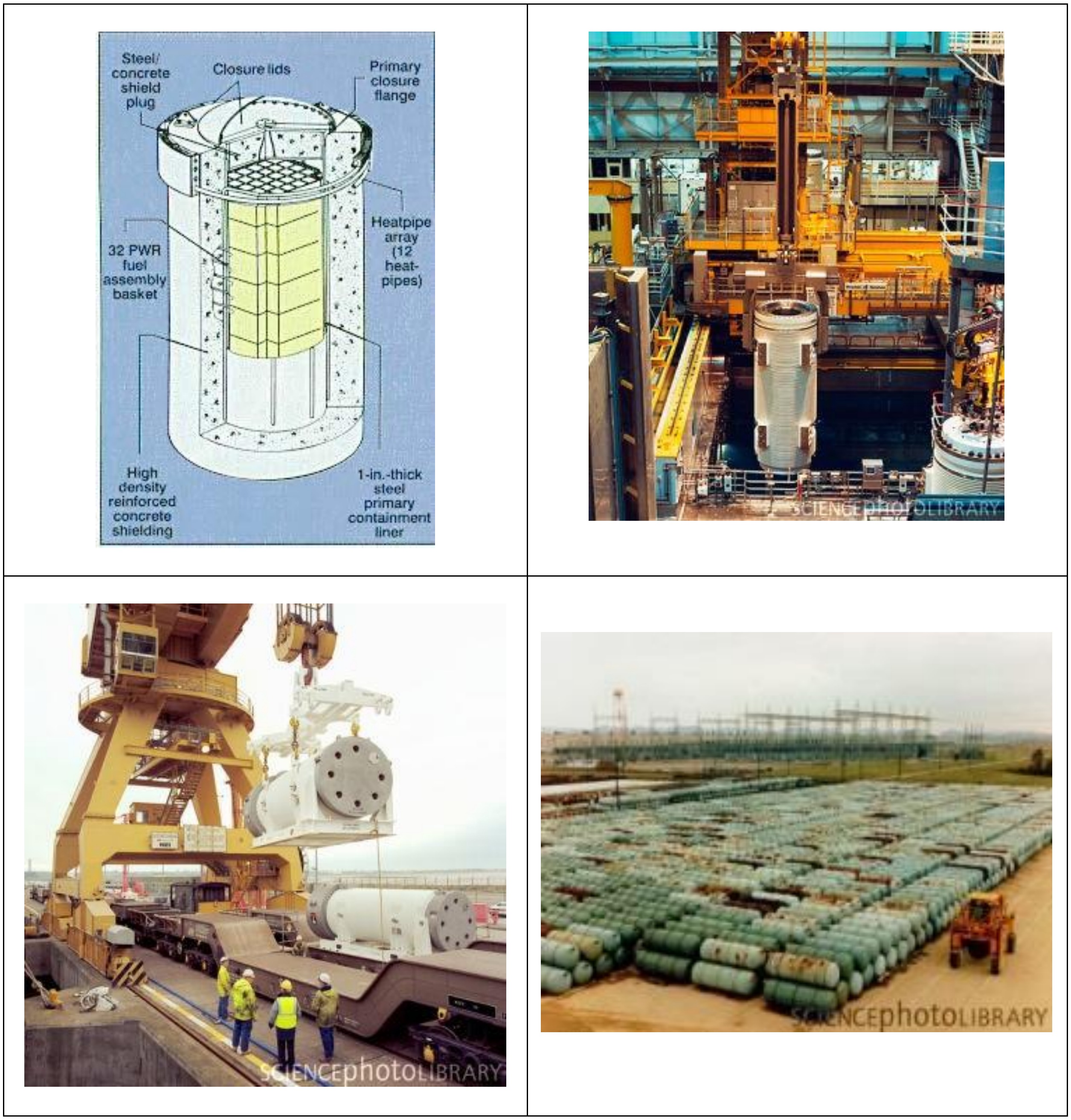


FIGURE 68

Dry Cask Storage

APPENDIX 1

Key Reactor Terms and Components

Fuel: The fissionable material contained in the reactor core that emits the heat needed to produce steam and, by extension, electricity.

Moderator: A material, either graphite or water (light or heavy), that slows down the neutrons in order to increase the fission probability and thus sustain the chain reaction.

Light Water: Normal H2O, consisting of molecules with 1 oxygen and 2 hydrogen atoms. Light water absorbs neutrons, which is why a water-cooled reactor requires enriched fuel. In a Light Water Reactor (LWR) the water can be used as both moderator and coolant.

Heavy Water: Chemically the same as light water, but both hydrogen atoms have been replaced by deuterium (hydrogen isotope with 1 proton and 1 neutron). Heavy water (D2O) slows down but does not capture neutrons as readily as light water, so it can be used as a moderator in reactors with natural (un-enriched) uranium fuel. Heavy water is naturally present in normal water, but in tiny amounts –about 1 part in 5,000.

Coolant: Circulating material, either gas or liquid (including molten metal), used to remove heat from the reactor core. The coolant is ether directly converts water to steam, or transfers heat to a secondary or tertiary loop where steam is created to drive a turbine or generator, which produces electricity.

Off-load: A reactor that is refueled while it is shut down, i.e., the facilities generators are disconnected from the electric grid and/or no heat is produced for utilization. Periods when off-load refueled reactors are shut down for refueling usually provide an opportunity for the International Atomic Energy Agency (IAEA) to verify the fuel in the reactor cores.

On-load: A reactor that does not have to be shut down for refueling and is refueled while producing power for electricity generation and/or heat utilization. Refueling on-load influences the design of IAEA safeguards approaches for facilities in respect of core fuel verification.

APPENDIX 2

Isotopic Composition of Nuclear Materials

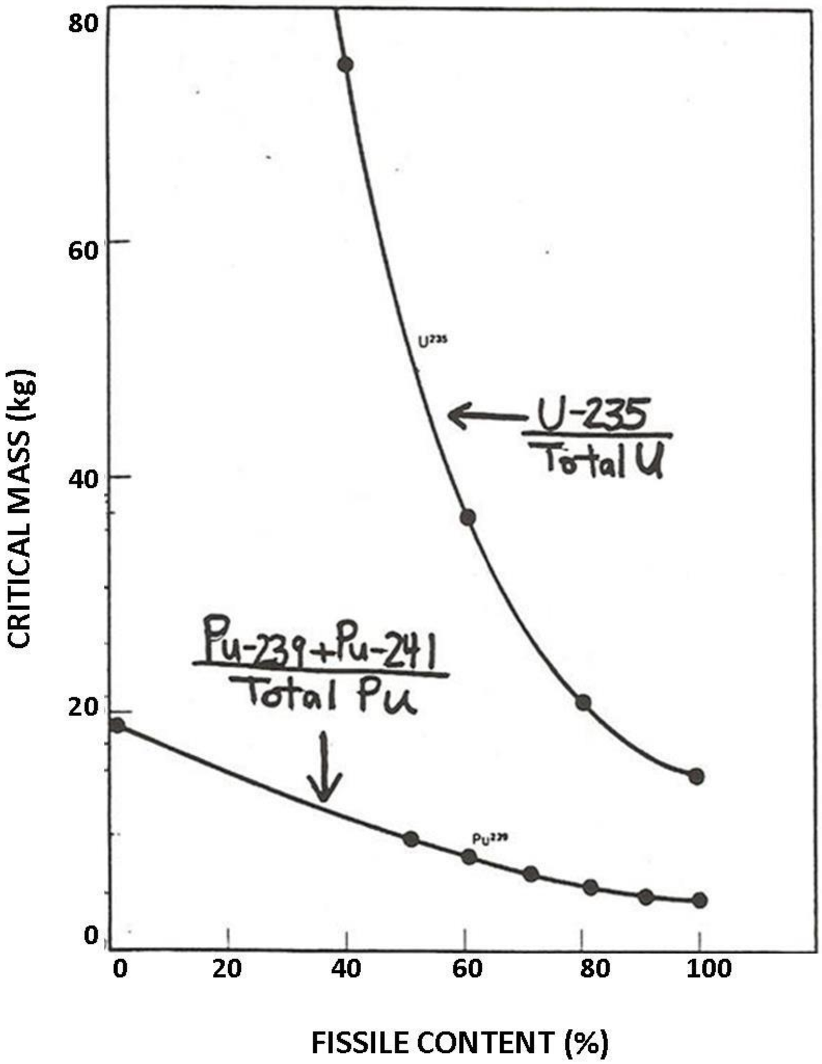
Isotopic* Composition of Uranium and Plutonium Used in Military and Civilian Applications (%)

	U-235	U-238	Pu-238	Pu-239	Pu-240	Pu-241	Pu-242
Natural Uranium	≥0.7	≤99.3	-	-	-	-	-
Depleted Uranium	0.2-0.5	>99.7					
Fresh LWR Fuel	3-5	95-97	-	-	-	-	-
Low-Enriched Uranium (LEU)	<20	>80	-	-	-	-	
Medium-Enriched Uranium (MEU)							
Highly Enriched Uranium (HEU)	≥ 20	≤80	-	-	-	-	-
Weapons-Grade Uranium (WGU)	93.5	6.5	-	-	-	-	-
Reactor-Grade Plutonium (RGPu)	-	-	1.5	58	24	11.5	5
Spent LWR Fuel	0.8	94	Total Pu=0.9%, with above isotopic content	“	“	“	“
Fresh Mixed-Oxide (MOX) LWR Fuel	0.2	96.8	Total Pu=3% with above isotopic content	“	“	“	“
Weapons-Grade Plutonium (WGPu)	-	-	-	93.5	6	0.5	-

*Atoms of same element with different mass and nuclear properties

APPENDIX 3

Critical Masses of Uranium and Plutonium as a Function of Isotopic Mix



Critical Mass (CM)

CM (U)

Infinite for $\frac{U235}{U} < \sim 10\%$

CM (Pu)

Finite for all isotopic mixes

APPENDIX 4

LWRs & Nonproliferation

The conventional wisdom among politicians, nuclear energy advocates, and nonproliferation experts is that LWRs are the best option for meeting rising global energy demands while being attentive to the risk of new states achieving the capability to create a nuclear weapon. LWRs are considered to be the most "proliferation resistant" and their construction by non-nuclear states is tolerated, if not supported, by many in the international community for several reasons.

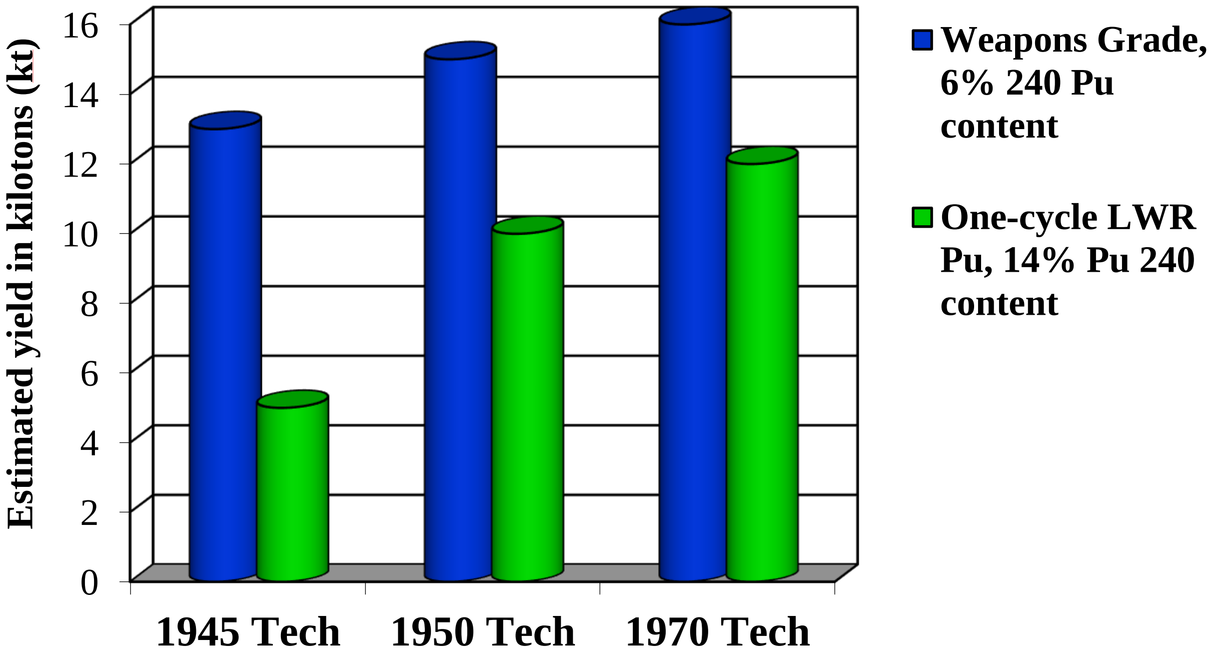
As discussed previously, LWRs must be shut down to access the accrued plutonium in the core, with the result that massive amounts of electricity production is kept off the national grid for weeks while the spent fuel is replaced. Second, the plutonium produced by LWRs is not considered optimal for making bombs and hence is believed to pose less of a threat. And third, LWRs require LEU for fuel. This requires the host state to either construct and operate, or have access to third-party conversion and enrichment facilities. Construction of the facilities to produce LEU is an expensive process which automatically reduces the risk of proliferation. On the other hand, a major supplier state could choose to deny future sales of LEU to a state that is suspected of illegally diverting materials for a weapon. The expectation is that a state wouldn't risk losing its supply of LEU by attempting to divert material, and that LWRs are thus the most "proliferation resistant." This helps explain why the U.S. approved the construction of LWRs in North Korea even after it was caught violating IAEA safeguards.

This perception of LWRs as the most "proliferation resistant" reactors is problematic for several reasons, however. Both the fresh and spent LWR fuel present cause for worry. To start with, approximately 20 tons of fresh LWR fuel, enriched to 3.5% U-235, is normally kept at the reactor site. This fuel can be de-cladded and the fuel pellets crushed and fluorinated just like natural uranium. This 3.5% solution of UF_6 can then be used as feed for further enrichment to weapons grade uranium with significantly less effort than it would take to achieve weapons grade status using natural uranium. Using natural uranium, 4,000 SWUs are required to enrich one bomb's worth (20kg) of HEU, but only 700 SWUs (equal to 1/5th the effort and time) is required to convert fuel already enriched to 3.5% U-235. This means that a state such as Iran could get enough material for its first bomb using LEU in only 8 weeks versus 12 months using natural uranium.

LWRs also can produce plutonium of any grade, including reactor-, fuel-, and weapons-grade. A nominal 1GWe plant will have produced 50-70 bombs' worth of reactor-grade plutonium when it is refueled in the first 12-18 months of operation. This reactor-grade material can be used to make nuclear weapons of a reliability and yield quite close to that of weapons-grade plutonium.

In addition, any LWR can be operated to produce weapons-grade plutonium in large amounts. For example, at the height of the Cold War, President Ronald Reagan proposed acquiring an LWR in Washington State in order to increase U.S. production of plutonium for weapons.[15]

**Estimated Yields for Different Bomb Technologies
Using LWR Pu**



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15. See Milton Hoenig, "Energy Department Blurs the Line Between Civilian, Military Reactors," *The Bulletin of the Atomic Scientists,* June 1987, pp. 25-27, available at http://books.google.com/books?id=pQYAAAAAMBAJ&pg=PA25&dq=wppss+weapons+plutonium+production+doe&hl=en&sa=X&ei=yISkU7mvB9froAS5_YKoCQ&ved=0CCQQ6AEwAQ#v=onepage&q=wppss%20weapons%20plutonium%20production%20doe&f=false; and U.S. Congress, House Subcommittee on General Oversight and Investigations, Committee on Interior and Insular Affairs, *Potential Conversion of WPSS 1 Nuclear Powerplant to a Production Reactor*, Hearing held in Portland, OR, December 7, 1987, Serial No. 100-42 (Washington, DC: USPO, 1988), available at http://babel.hathitrust.org/cgi/pt?id=pst.000014315848;view=1up;seq=1

APPENDIX 5

IAEA Safeguards

To be truly effective at preventing proliferation, safeguards need to be administered during every stage at which potential nuclear weapons material can be diverted from the energy cycle to weapons production. This includes mining, conversion, enrichment, fuel fabrication, energy production, reprocessing and fuel storage. The objective of Non-Proliferation Treaty (NPT) safeguards is defined as the "***timely detection*** *of the diversion of* ***significant quantities*** *of nuclear material from peaceful nuclear activities to the manufacture of nuclear weapons or of other nuclear explosive devices or for purposes unknown, and deterrence of such diversion by the risk of early detection*." The terms "timely detection" and "significant quantities" have had to be translated by the IAEA into quantitative goals for effective implementation of safeguards. These goals are guidelines for the development of safeguard approaches.

Significant Quantity

"The approximate quantity of nuclear material in respect of which, taking into account any conversion process involved, the possibility of manufacturing a nuclear explosive device cannot be excluded."

Timeliness Goal

Derived from the conversion time, the timeliness goal is the time required to convert different forms of nuclear material to metallic components of nuclear explosive devices given that the necessary facilities (and skills) exist.

Direct Use Materials	**Significant Quantity**
Pu	8 kg total element (containing less than 80% Pu-238)
U-233	8 kg total isotope
HEU	25 kg contained U-235

Indirect Use Materials	**Significant Quantity**
LEU (U-235 <20%)	75 kg contained U-235 (include natural and depleted U)
Thorium	20 tons total element

Material	**Timeliness Goal**
Non-irradiated direct use (e.g. Pu in fresh fuel)	One Month
Irradiated direct use (e.g. Pu in spent fuel)	Three Months
Indirect use (e.g. LEU)	One Year

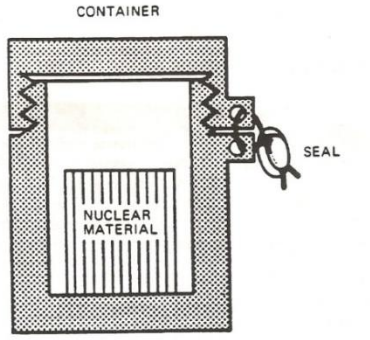
APPENDIX 6

Basic IAEA Safeguards Methods

To assure that diversions of significant quantities of material cannot occur without timely warning, the IAEA employs a number of methods such as containment and surveillance.

Containment

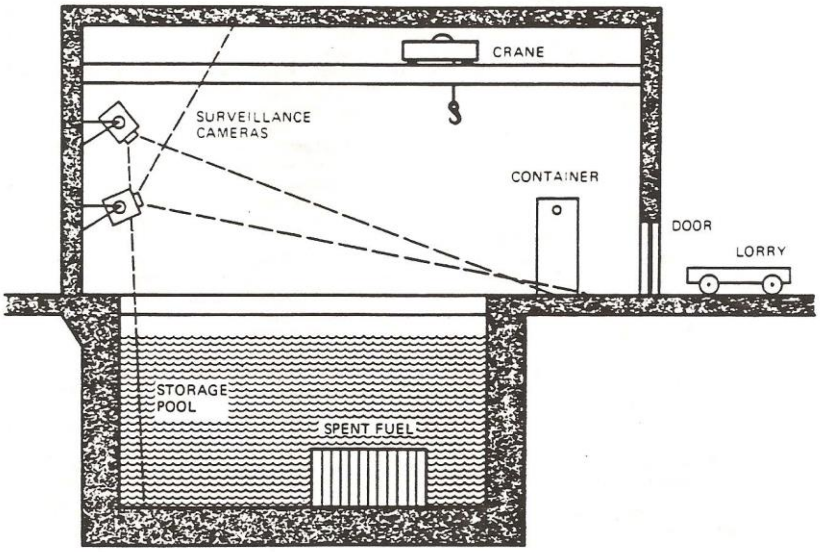
Structural features of a facility or equipment which enable the IAEA to establish the physical integrity of an area of item by preventing undetected access or movement of nuclear material or interference with the item or IAEA safeguards equipment or data. Continuing integrity of the containment is usually assured by security seals or surveillance.



Containment measures: application of seal.

Surveillance

The collection of information aimed at the monitoring of the movement of nuclear material and the detection of interference with containment and tampering with IAEA safeguards devices, samples and data. Methods include human, video, and photographic observation.



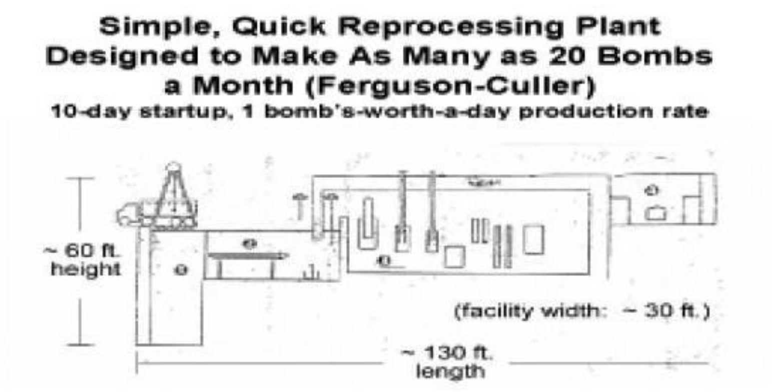
Combined application of containment and surveillance.

In the case of plutonium, the IAEA will sample a number of fuel rods, assemblies, and cans of spent fuel by weighing them and assessing the amount of gamma ray radiation they are producing. Depending on the number of samples inspected, the likelihood IAEA detecting a diversion varies.

Detection Probability (%)	**Number of samples inspected (out of 100 total samples)**
95	53
90	44
75	29
60	21
50	16
40	12
25	7

APPENDIX 7

Fuel Making & Safeguards



Reprocessing: Although the PUREX plant at Hanford is immense, there are other plans for small, covert reprocessing plants, such as the Ferguson-Culler design shown at left, that could produce—assuming a 10 day start-up period and an average rate of 1 bomb's worth of material per day—20 or more bombs each month from spent reactor fuel.

Aside from the threat of covert facilities, it is difficult enough to keep track of declared reprocessing activities at authorized facilities. For example, past safeguard verification problems included:

Sellafield (UK)
29.6 kg Pu MUF (material unaccounted for) Feb. 2005
190 kg Pu in "leak" undetected for 8 months
Cogema-Cadarache (France)
Euratop report 2002, "unacceptable amount of MUF," 2yrs to resolve

Tokai Mura (Japan)
MOX, 69 kg Pu MUF (1994)
Scrap 100-150 kg Pu MUF (1996)
Pilot reprocessing 206 kg - 59 kg Pu MUF (2003)
Commercial reprocessing 246 kg/yr Pu MUF (2008?)

The receipt hall of a reprocessing plant in the UK is shown at left. On the right, a container of highly radioactive waste nuclear fuel is prepared for interim storage in the cooling pool.