The Nuclear Lexicon Project: Breaking down the Complexities of Nuclear Science for Policymakers

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Based in Honolulu, the Pacific Forum CSIS (www.pacforum.org) operates as the autonomous Asia-Pacific arm of the Center for Strategic and International Studies in Washington, DC. The Forum's programs encompass current and emerging political, security, economic, business, and oceans policy issues through analysis and dialogue undertaken with the region's leaders in the academic, government, and corporate arenas. Founded in 1975, it collaborates with a broad network of research institutes from around the Pacific Rim, drawing on Asian perspectives and disseminating project findings and recommendations to opinion leaders, governments, and members of the public throughout the region.

The Young Leaders Program

The Young Leaders Program invites young professionals and graduate students to join Pacific Forum policy dialogues and conferences. The program fosters education in the practical aspects of policy-making, generates an exchange of views between young and seasoned professionals, promotes interaction among younger professionals, and enriches dialogues with generational perspectives for all attendees. Fellows must have a strong background in the area covered by the conference they are attending and an endorsement from respected experts in their field. Supplemental programs in conference host cities and mentoring sessions with senior officials and specialists add to the Young Leader experience. The Young Leaders Program is currently supported by Chevron, the Henry Luce Foundation, the Sasakawa Peace Foundation, and the Yuchengco Group, with a growing number of universities, institutes, and organizations also helping to sponsor individual participants. For more details, see the Pacific Forum CSIS website, www.pacforum.org, or contact Brad Glosserman, director of the Young Leaders Program, at brad@pacforum.org.

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Introduction

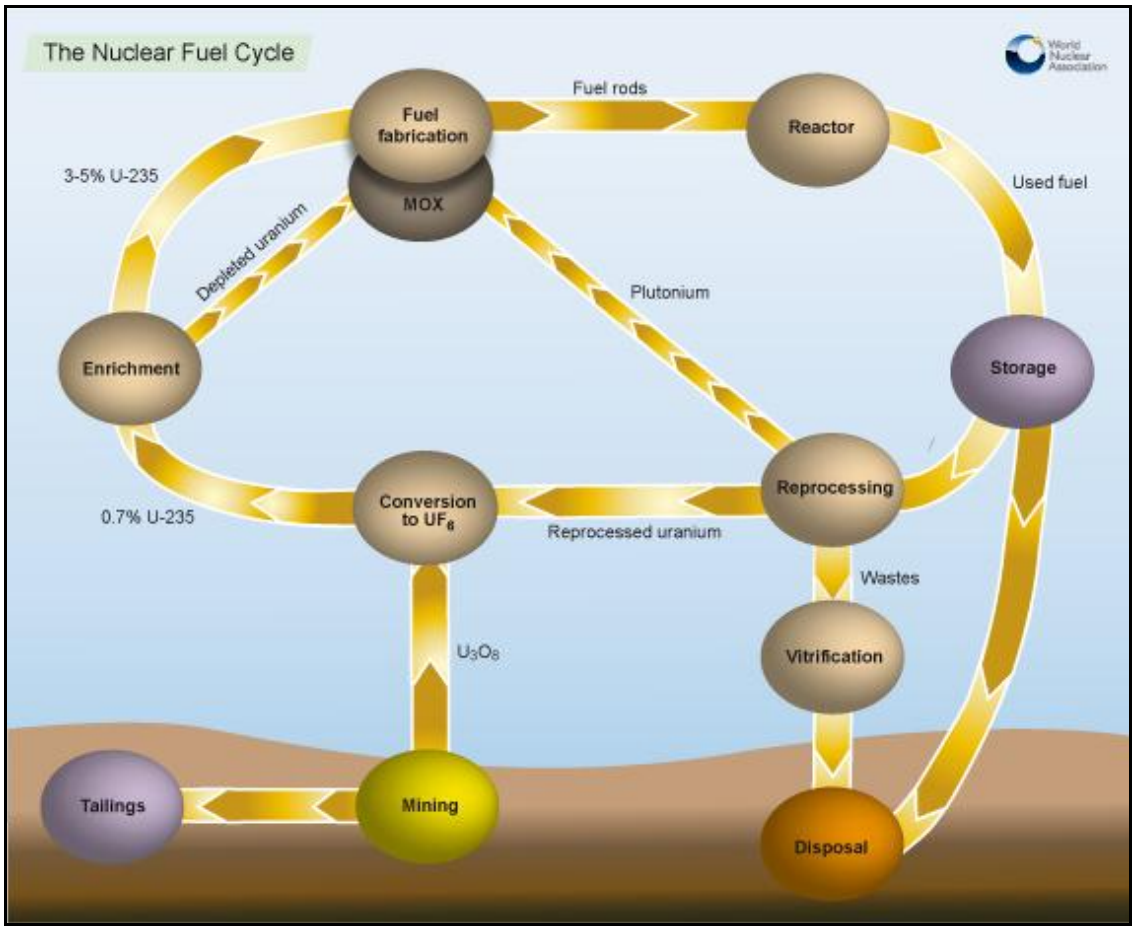
By Natasha Barnes, Brittany Billingsley, Sungmin Cho, Mark Garnick, Nadezda Larsen, Trang Thuy Le, David Lin, Rebecca Neame, Huong Phu Tan Nguyen, Naoko Noro, David Santoro, Adrian Yi, and Philip Zhang

On July 3-4, 2010, members of the Pacific Forum CSIS Young Leaders program attended the Council for Security Cooperation in the Asia Pacific (CSCAP) Study Group on Countering the Proliferation of Weapons of Mass Destruction in the Asia Pacific. In speaking with a number of specialists, we found that a complete understanding of nuclear security issues facing the Asia-Pacific region, required knowledge of science. Young Leaders thus decided to develop a practical resource to bridge the gap between security policy practitioners and the oftentimes technical and scientific terminology of nuclear weapons and nonproliferation.

This effort manifested itself in Nuclear Lexicon Project, designed to serve as a basic guide to the key concepts surrounding nuclear weapons, their development, use, storage, and security. Intended as an on-going work in progress, the Nuclear Lexicon Project attempts to break down these concepts into digestible and accessible definitions for policymakers and academics alike. It is the hope of the Young Leaders who initiated the project that it continues and is added to by current and future participants as the science and policy evolves to become more comprehensive with time.

The Nuclear Lexicon Project: Breaking down the Complexities of Nuclear Science for Policymakers

The Nuclear Fuel Cycle



Graphic 1: "The Nuclear Fuel Cycle," http://www.world-nuclear.org/info/inf03.html

The term 'nuclear fuel cycle' refers to the series of industrial processes by which natural uranium ore becomes reactor or weapons usable fuel, and then nuclear waste. The fuel cycle is divided into three components: the front end, which encompasses all activities before the fuel is placed into the nuclear reactor; the service period, which is when the fuel is converted into energy in the reactor; and the back end, which incorporates all processes involving spent fuel. The fate of the spent fuel determines whether the fuel cycle is *closed* or *open.* In the closed cycle, the spent fuel is reprocessed, whereas in the open cycle, it is sent to long-term storage. To date, the United States has opted for the open cycle, while France, the United Kingdom, Russia, China, and Japan reprocess spent fuel.

Stage 1: Mining and Milling

Uranium Mining

Uranium mining refers to the very first stage of the nuclear fuel cycle. In order to get uranium, which occurs naturally in the earth's crust, quantities of uranium ore are mined with different techniques. Because the amounts of uranium dispersing in the earth's crust vary greatly, from 1 to 500,000 parts per million (averaging out at 2.8 to 3 parts per million),[1] an orebody usually has to contain over 0.1 percent (i.e., 1000 parts per million) uranium content in order to be economically viable for mining. Although in some rare cases very low-grade ores – containing as little as 0.02 percent uranium – can successfully support mining operations, the average grade of uranium concentration has been increasing up to 20 percent in some of today's ores.[2]

Uranium is a heavy, naturally occurring radioactive element, primarily consisting of two isotopes – uranium-235 (U-235) and uranium-238 (U-238). Only the former of these two is capable of sustaining a fission reaction. Natural uranium is about 0.7 per cent U-235 and 99.3 per cent U-238. The largest known deposits are found in Australia. Canada, Russia and Kazakhstan also hold significant amounts.

Depending on the geological location of the orebody, surface or underground mining technique will be employed to extract uranium deposits:

- *Surface/Open-cut mining* method is often used for orebodies located near the surface. This involves extracting rock containing uranium oxide (U_3O_8) from large open pits, crushing and grinding the rock, and leaching the crushed rock with sulphuric acid to separate uranium from overlying/waste rock.[3]

- *Underground mining method* helps extracting uranium from orebodies that lie far below the surface. Shafts and tunnels are dug to provide access to uranium ores, which will then be milled with sulphuric acid to recover uranium from waste material.[4]

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[1] The World Nuclear Association estimates the average concentration of uranium in the earth's crust is 2.8 parts per million; the Federation of American Scientists puts the number at 3 parts per million. See "Uranium mining," World Nuclear Association (WNA), http://www.world-nuclear.org/education/mining.htm (accessed July 25, 2010) and "Uranium mining and milling," Federation of American Scientists (FAS), http://www.fas.org/programs/ssp/nukes/fuelcycle/miningmilling.html (accessed July 25, 2010).

[2] "Uranium mining," World Nuclear Association (WNA); Peter Diehl, "Uranium mining and milling wastes: An introduction," World Information Service on Energy Uranium Project (WISE Uranium Project), August 15, 2004, http://www.wise-uranium.org/uwai.html (accessed July 25, 2010).

[3] "Uranium mining," World Nuclear Association (WNA); "Uranium mining and milling," Federation of American Scientists (FAS).

[4] "Uranium mining," World Nuclear Association (WNA); "The nuclear fuel cycle," Australian Nuclear Science and Technology Organization (ANSTO), *The nuclear fuel cycle*,

- *In-situ leach (ISL) mining* technique is applied when the orebody lies in groundwater in permeable material (e.g., gravel, sand, etc.). After a leaching liquid (e.g., ammonium-carbonate or sulfuric acid) has been injected into groundwater to dissolve uranium, the uranium-containing solution is pumped to the surface and processed to recover the uranium as a precipitate.[5]

Many indigenous populations have been severely affected by mining and milling operations, which pose serious health hazards including lung cancers (due to inhaling uranium decay products) and food/water poisoning (due to seepage and spills from tailings piles).[6]

Yellowcake

Graphic 2: A drum of yellowcake, http://en.wikipedia.org/wiki/Yellowcake

Uranium ore needs to undergo the process of milling, conversion, enrichment, and fabrication before it is made into fuel to be used in a reactor. Yellowcake is a mixture of uranium oxides (U_3O_8) which is produced after the uranium milling process.[7]

Yellowcake contains 70 to 90 percent U_3O_8. It is called "yellowcake" because of its yellow (or khaki) color; however, the color can vary from yellow to blackish green depending on the temperature at which the material is dried. Then the yellowcake is converted into uranium hexafluoride in a conversion plant.

Although yellowcake itself cannot be used for nuclear power fuel or a dirty bomb without intensive enrichment processes, there are proliferation risks associated with yellowcake. As such, countries which have ratified the IAEA Additional Protocol are required to declare their yellowcake stockpiles to IAEA.[8]

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http://www.ansto.gov.au/nuclear_information/managing_nuclear_materials/the_nuclear_fuel_cycle (accessed July 25, 2010).

[5] "Uranium mining," World Nuclear Association (WNA); Diehl, "Uranium mining and milling wastes: An introduction."; "Uranium: Its uses and hazards," Institute for Energy and Environmental Research (IEER), http://www.ieer.org/fctsheet/uranium.html (accessed July 25, 2010)

[6] "Uranium: Its uses and hazards," Institute for Energy and Environmental Research (IEER).

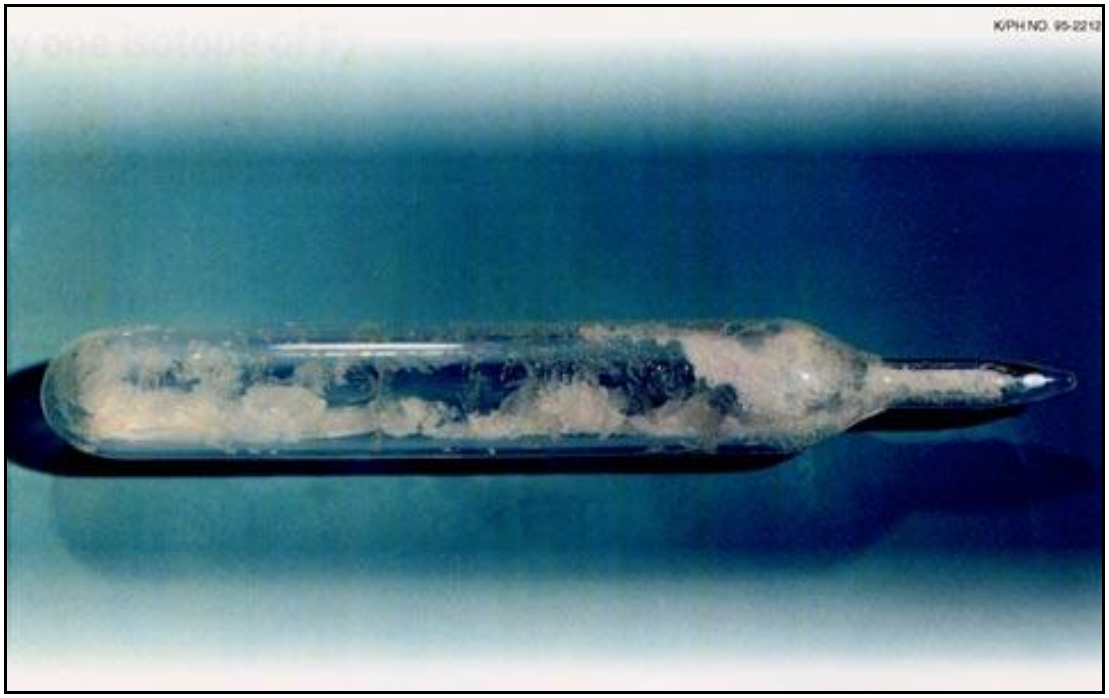
[7] "Yellowcake," United States Nuclear Regulation Commission, August 2, 2010, http://www.nrc.gov/reading-rm/basic-ref/glossary/yellowcake.html (accessed August 4, 2010).

[8] Sasha Henriques, "Where It All Begins," International Atomic Energy Agency, http://www.iaea.org/Publications/Magazines/Bulletin/Bull512/51203413841.pdf (accessed July 27, 2010).

Stage 2: Conversion

Uranium Hexafluoride

Uranium hexafluoride (UF_6) is referred to as "hex" in the nuclear industry. It is a chemical compound that consists of one atom of uranium combined with six atoms of fluorine. It is the form of uranium used during the uranium enrichment process that produces fuel to be used either in nuclear reactors or nuclear weapons. It is used in uranium processing because it can be a solid, liquid, or a gas, and can therefore be used as a gas for processing, a liquid for filling or emptying containers, or as a solid for storage.



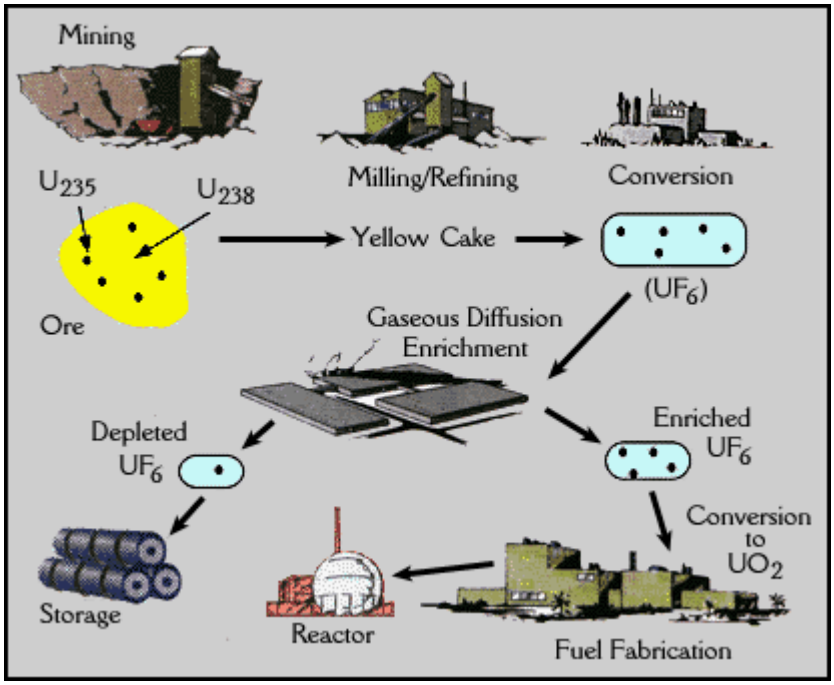
Graphic 3: UF_6 crystals in a glass, http://web.ead.anl.gov/uranium/guide/uf6/index.cfm

UF_6 production proceeds as follows. Uranium ore (U-235 or U-238) is mined and then sent to a mill or refinery that produces uranium oxide ("yellowcake"). The "yellowcake" is then combined with anhydrous HF and fluorine gas to form UF_6, which is placed into steel cylinders, and sent as a solid to a gaseous diffusion plant to be enriched through either the gaseous diffusion or centrifuge methods (see below for details about each methods).

Hydrogen Fluoride (HF), is a chemical compound of hydrogen and fluorine. "**Anhydrous**" simply means that the compound does not contain water.

The conversion of uranium oxide into UF_6 is significant because it is the ultimate step before enrichment, a key step toward developing nuclear weapons, although uranium enrichment is also widely used in the civilian sector.

Stage 3: Enrichment



Graphic 4: Uranium, from Ore to Reactor Fuel,
http://web.ead.anl.gov/uranium/guide/uf6/index.cfm

Uranium Enrichment

Natural uranium consists of three isotopes: uranium-238 (U-238), uranium-235 (U-235) and uranium-234 (U-234).[9] Uranium enrichment increases the proportion of U-235 via the process of isotope separation in order to yield significant amounts of energy.

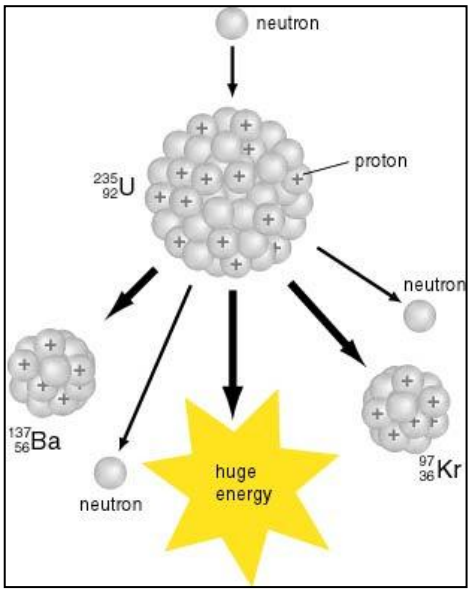
Summary of Uranium Isotopes				
Isotope	**Percent in natural uranium**	**Number of Protons**	**Number of Neutrons**	**Half-Life (in years)**
Uranium-238	99.284	92	146	4.46 billion
Uranium-235	0.711	92	143	704 million
Uranium-234	0.0055	92	142	245,000

Table 1: "Uranium: Its Uses and Hazards," Institute for Energy and Environmental Research, http://www.ieer.org/fctsheet/uranium.html

[9] "Uranium: Its uses and hazards," Institute for Energy and Environmental Research (IEER).

Low-enriched uranium (LEU) has a less than 20 percent concentration of U-235. Commercial light water reactors require LEU that has been enriched from 3 to 5 percent U-235, whereas research reactors use fresh LEU enriched around 12 to 19.75 percent U-235.

Highly-enriched uranium (HEU) has a greater than 20 percent concentration of uranium-235. Nuclear weapons using fissile uranium are divided into two types: weapons-grade, with at least 85 percent of U-235, and weapons-usable, with about 20 percent of U-235. The greater the proportion of U-235, the less material is needed to cause a nuclear detonation.



Graphic 4: Uranium-235 in the process of isotope separation, "Enrichment: Visualizing the Value Function," http://energyfromthorium.com/wp-content/uploads/2010/08/U235_fission.jpg

Why is HEU a threat?

In 2002, the United State National Research Council said that "crude HEU weapons could be fabricated without state assistance,"[10] and noted the need to prevent countries or technically-competent terrorist groups from developing nuclear weapons with HEU.

Since 1978, when the US initiated the reduced enrichment for research and test reactors program, international joint efforts have been made to minimize and eventually eliminate reliance on HEU in the civilian fuel cycle, including conversion of research and test reactors worldwide from the use of HEU to the use of LEU fuel. At the end of 2003, it was estimated that there existed 50 tons of HEU in civilian power and research programs in over 50 nations. Many of them do not have adequate safety and security measures. The IAEA should assist them to improve their security, and supply technical arrangements to control and protect nuclear materials.

Dual-use technology

The term "dual-use technology" is primarily applied to technologies used for both military and peaceful aims. Its second meaning, in the context of potential weapons development, is more sophisticated as the knowledge and method to conduct legitimate research and manufacture nuclear weapons are difficult to differentiate. Recently, both Iran and North Korea announced their intentions to peacefully develop nuclear energy, and then were accused of developing nuclear weapons programs based on the presence of dual-use technology.

[10] "Why Highly Enriched Uranium is a Threat," Nuclear Threat Initiative (NTI), September 2009, http://www.nti.org/db/heu/index.html (accessed July 25, 2010).

Rapid advances in biology, chemistry, and information science have produced even more dual-use technologies. The IAEA has tried to monitor them in countries that signed the Nuclear Non-Proliferation Treaty (NPT) to make sure that fissile material is not diverted to military functions. Several international arrangements also seek to harmonize lists of dual-use technologies to control, such as the Nuclear Suppliers Group the Missile Technology Control Regime (MTCR) and the Wassenaar Arrangement.

Fissile Material[11]

Fissile material refers to an isotope that can be broken apart through the nuclear fission process by capturing extra thermal neutrons. As such, materials such as natural or depleted uranium that have not been irradiated and materials irradiated in thermal reactors alone are not considered fissile.

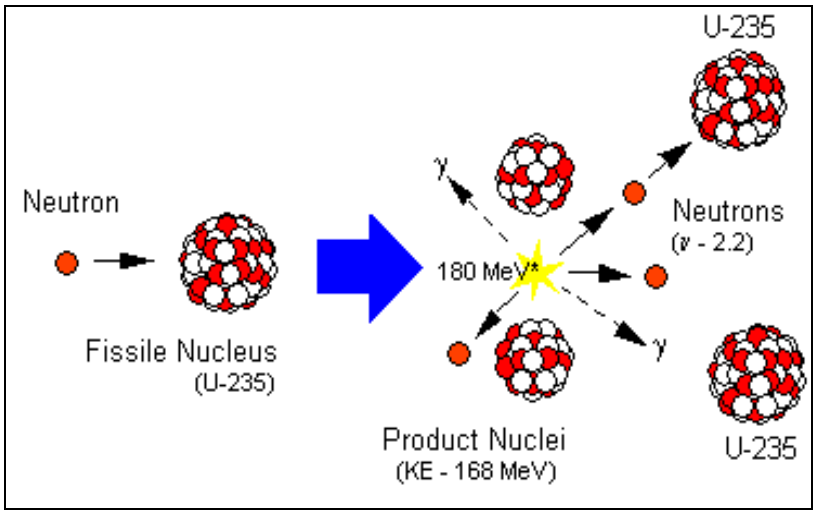
The three key fissile materials, for both nuclear energy and weapons, are U-233, U-235 and Pu-239. When these materials are used in nuclear reactors, the split is controlled and the energy is harnessed for civilian purposes – largely electricity generation. In weapons, the split occurs all at once and the massive amount of released energy results in an explosion.

Isotopes (or 'nuclides') are atoms of various elements with different numbers of neutrons. For instance, uranium-233 and uranium-235 are both atoms of uranium, but they have different numbers of neutrons (141 and 143 respectively), and are therefore different isotopes.

The **nuclear fission** process occurs when an isotope is broken apart to release energy. For a more detailed explanation, see our discussion on the topic.

Thermal neutrons are low-energy, slow-moving neutrons that are not bound to an atom (and are therefore free-floating). They are particularly desirable for certain chain reactions like fission.

[11] United States Nuclear Regulatory Commission (NRC), "Fissile Material," March 8, 2010, http://www.nrc.gov/reading-rm/basic-ref/glossary/fissile-material.html (accessed July 23, 2010); Institute for Energy and Environmental Research, "Fissile Material Basics," May 20, 1996, http://www.ieer.org/fctsheet/fm_basic.html (accessed July 23, 2010); United States Nuclear Regulatory Commission (NRC), "Nuclide," March 8, 2010, http://www.nrc.gov/reading-rm/basic-ref/glossary/nuclide.html (accessed July 23, 2010).



Graphic 5: Fission of Uranium-235, from "Space Power," National Aeronautics and Space Administration (NASA), http://science.nasa.gov/science-news/science-at-nasa/2002/03sept_spacepower/

Because fissile material can be used for civilian or weapons purposes, its presence raises concerns regarding a country's potential nuclear weapons program and/or its proliferation history. This has led to a number of efforts to curb the spread of fissile material for weapons-related or *potential* weapons-related usage via international cooperation, agreements, and initiatives. These include the IAEA and the Nuclear Nonproliferation Treaty safeguards frameworks, regional initiatives (e.g., the Southeast Asian Nuclear Weapons Free Zone (SEANFWZ)), export controls, and efforts to improve and maintain the physical protection of both nuclear material and facilities.[12]

Graphic 6: "Uranium-235," Wikipedia, http://en.wikipedia.org/wiki/Uranium-235

[12] "Agreements and Institutions to Control Fissile Materials," International Panel on Fissile Materials (IPFM), http://www.fissilematerials.org/ipfm/pages_us_en/fissile/agreements/agreements.php (accessed July 23, 2010).

Fissile vs. Fissionable Material[13]

Fissionable material is sometimes used interchangeably with *fissile* material – it refers to isotopes that can be split via nuclear fission; however, there are important differences. While fissile material *only* refers to materials that can be split by 'slow' neutrons, fissionable material includes isotopes which can be split by 'fast neutrons.' These materials also include isotopes that can be broken apart by 'fast neutrons' in addition to thermal neutrons. Key fissionable materials (in addition to the ones above) are thorium-232 (Th-232), U-238, and plutonium-240 (Pu-240).

Fast neutrons are free, high-energy neutrons that maintain a higher kinetic energy than that of their surroundings and are thus 'faster' than their thermal counterparts.

Another difference between fissile and fissionable material is the "Odd/Even Effect." While fissile materials can take on an additional low-energy neutron to fission, *fissionable* materials are more stable with an even number of neutrons/protons, and so need a greater amount of 'binding energy' to undergo nuclear fission. When a neutron is added to an isotope with an odd number of neutrons (as is the case with fissile materials), a significantly greater amount of energy is produced – which is why thermal neutrons are enough to kick-start the process. However, when a neutron is added to an isotope that already has an even number of neutrons, not enough energy is produced for the isotope to fission. Therefore, more energy needs to be possessed by the neutron for the chain reaction to occur.

As was the case with fissile material, the presence of fissionable material raises concerns about weapons programs and potential proliferation risks. Because of their dual-use nature (for civilian purposes or weapons), the concern surrounding diversion, loss, or theft of fissionable materials has encouraged the international community to prevent or at the very least control their spread.

[13] United States Nuclear Regulatory Commission (NRC), "Fissionable Material"; "Fissionable Material," Nuclear Power Fundamentals, Integrated Publishing, http://www.tpub.com/content/doe/h1019v1/css/h1019v1_75.htm (accessed July 23, 2010); United States Nuclear Regulatory Commission (NRC), "Fast Neutron," May 20, 2010, http://www.nrc.gov/reading-rm/basic-ref/glossary/fast-neutron.html (accessed July 23, 2010).

Significant Quantity (SQ)[14]

"Significant Quantity" (SQ) refers to the minimum average amount of nuclear material needed to leave open the option of creating a nuclear explosive device (see the Nuclear Weapons section for examples of such devices). According to the International Atomic Energy Agency (IAEA), the SQ of these materials is as follows:

Direct use nuclear material refers to materials that can be manufactured into nuclear explosive devices without further enrichment or chemical "transmutation."

Meanwhile, **indirect use nuclear material** refers to everything else (i.e., depleted uranium, natural and low-enriched uranium, thorium), all material which must be further processed in order to produce *direct* use nuclear material.

Fissile Material	Significant Quantity
Direct use nuclear material	
Plutonium (containing less than 80% plutonium-238)	8 kg
Uranium-233	8 kg
HEU (uranium containing more than 20% uranium-235)	25 kg of U-235
Indirect use nuclear material	
LEU (containing less than 20% of uranium-235)	75 kg of contained U-235
Natural uranium	10 tons
Depleted uranium	20 tons
Thorium	20 tons

Table 2: 'Significant Quantities' from the "IAEA Safeguards Glossary"

Because the SQ represents the "minimum amount" of nuclear material that could be used to manufacture a "nuclear explosive device" if diverted from civilian nuclear programs, the IAEA uses this number to assess proliferation risks during safeguards inspections. The SQ are the base-line against which other countries' and non-state actors' ability to construct a nuclear weapon are measured, and are therefore tied not only to the IAEA's safeguard agreements and initiatives but also to global nonproliferation efforts. If a country or non-state actor can gain SQ of nuclear material – direct use nuclear material in particular – then they can gain de facto nuclear weapons capability. [15]

[14] "Agreements and Institutions to Control Fissile Materials," International Panel on Fissile Materials (IPFM); "IAEA Safeguards Glossary," International Atomic Energy Agency, *International Nuclear Verification Series* 3 (2001), http://www-pub.iaea.org/MTCD/publications/PDF/nvs-3-cd/PDF/NVS3_prn.pdf (accessed July 26, 2010), 23, 33 and 34.

[15] "Agreements and Institutions to Control Fissile Materials," International Panel on Fissile Materials (IPFM); Thomas B. Cochran and Christopher E. Paine, "The Amount of Plutonium and Highly-Enriched Uranium Needed for Pure Fission Nuclear Weapons," Natural Resources Defense Council (NRDC), Washington DC, April 13, 1995, http://www.nrdc.org/nuclear/fissionw/fissionweapons.pdf (accessed July 26, 2010), 1-2.

However, there is some debate about what should be considered the "actual minimum" amount of nuclear material required for a weapon. Within the scientific community, some insist that the current estimates used by the IAEA were based on now outdated information, and that the SQ is roughly half the currently established amounts. This is important as it lowers the threshold at which the international community needs to start worrying about the proliferation risk tied to a country's nuclear program.

Plutonium

Plutonium is a man-made radioactive element, produced as a by-product in some nuclear reactors when a U-238 atom absorbs a neutron from a U-235 atom. With an additional neutron, it becomes U-239, which then decays to neptunium (half life of 24 minutes) and then plutonium-239 (Pu-239).

The isotopic composition of plutonium in spent fuel varies depending on the type of reactor. For example, a light-water reactor (LWR) produces spent fuel with 50-70 percent Pu-239 and 25 percent Pu-240, a composition referred to as "reactor-grade" plutonium. In contrast, a heavy-water reactor (HWR) can be used to produce spent fuel with a plutonium concentration of 90 percent or greater, also known as "weapons-grade" plutonium. Designers of nuclear weapons prefer to use plutonium with a high concentration of Pu-239, as it generates a lower rate of radioactive heat with fewer emissions of neutrons and gamma rays, making it easier and safer to handle.

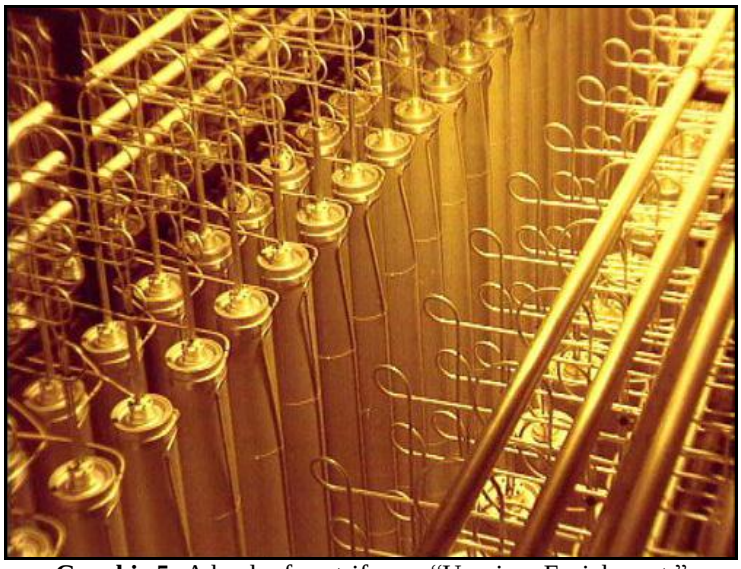
Centrifuge

There are two dominant techniques for uranium enrichment: gaseous diffusion and centrifuge enrichment. Centrifuge enrichment exploits the mass difference of U-235 and U-238. The capacity of enrichment is measured in terms of "separative work units (SWU)," a unit of measurement of the energy needed to separate U-235 and U-238. Centrifuge enrichment is considered more energy-efficient than gaseous diffusion since it requires only about 50-60 kWh per SWU, while gaseous diffusion requires 2400 kWh per SWU.

The UF_6 gas is fed into a series of vacuum tubes, and when the tubes are spun rapidly, heavier U-238 increases in concentration toward the outer edge of the cylinder, and lighter U-235 increases in concentration toward the center of the cylinder. The centrifuge needs to be arranged in cascade to increase the capacity of isotope separation.

Natural uranium contains only 0.7 percent of fissile uranium, U-235, and remaining 99.7 percent is mostly U-238, which is not fissile. The uranium needs to be "enriched" up to 3-5 percent to be used as fuel for reactors.

A centrifuge provides for the production of not only uranium for nuclear fuel but also weapon-grade highly enriched uranium. The proliferation of centrifuge designs, technologies, and equipment poses enormous problems for the non-proliferation regime.



Graphic 5: A bank of centrifuges, "Uranium Enrichment," http://www.world-nuclear.org/info/inf28.html

Laser Enrichment

Laser enrichment techniques offer considerable economic advantages because energy inputs and capital costs are low. Existing techniques are under investigation or under development — none of them are used commercially yet. The three current laser enrichment techniques include the atomic vapor isotope separation (AVLIS), the molecular laser isotope separation (MLIS), and the separation of isotope by laser excitation (SILEX).

AVLIS uses lasers tuned to frequencies that ionize exclusively a U-235 atom; U-235 ions are then attracted and collected. The AVLIS method offers high energy efficiency, high separation factor, and a low volume of radioactive waste.

The MLIS method uses tuned lasers to separate isotopes of uranium in a similar manner to AVLIS. But it consumes less energy and uses uranium hexafluoride instead of vaporized uranium, operating in the same way as the gaseous diffusion method.

SILEX also uses UF_6, but details of the process are not public; they are restricted by intergovernmental agreements between the United States and Australia (it was initially developed in Australia). The method is reportedly more efficient than other laser enrichment production techniques. Two years ago, one of the commercial entities involved moved forward with the intention to launch the first potential commercial uranium enrichment facility using SILEX. But concerns have been raised about the threat to global nuclear security that the process poses: it requires up to 75 percent less space and consumes much less energy than current enrichment methods, making it undetectable by national technical means from orbit.

Stage 4: Fuel Fabrication

MOX Fuel[16]

Mixed oxide (MOX) fuel is comprised of plutonium dioxide (PuO_2) and depleted uranium, which is equivalent to using 4.5 percent enriched U-235, and is used in commercial nuclear power plants. In light-water reactors (LWR), PuO_2 is combined with uranium dioxide (UO_2). The powder created by the combination of plutonium and uranium components is then fabricated into a cylinder, which is then placed in a metallic pan, and heated to below its boiling point until the powder adheres to itself. This produces pellets that are placed in an alloy cladding tube. Once the tube is filled, it is welded shut. The tube is assembled in a fuel rod, and used in a nuclear reactor. MOX fuel increases the energy gathered by over 12 percent compared to regular reactor-grade plutonium, Pu-240. If it is recycled, then the energy output becomes 22 percent greater compared to regular reactor-grade plutonium.

MOX fuel also provides a useful option in disposing of weapons-grade plutonium, as it can be created from the plutonium recovered from used fuel rods. Currently, no states are permitted to reprocess spent MOX fuel, but are to store it until Generation VI Fast Breeder Reactors are developed. MOX fuel will be useful in eliminating stockpiles of plutonium, and will greatly assist a Fissile Material Cut-Off Treaty (FMCT). However, some of the challenges of MOX fuel include storage, and developing the capability.

PWR Fuel[17]

Pressurized water reactor (PWR) fuel is made of four-meter-long pressurized, cylindrical Zircaloy tubes filled with uranium oxide (UO_2) pellets. There are roughly 179-264 tubes per bundle, and roughly 121-193 of these bundles are loaded into the reactor's core. Control rods are then inserted from the top into the fuel rod bundle.

Zircaloy is a high-zirconium alloy with a very low absorption for thermal neutrons. As such, it's often used as cladding (i.e., outer layer) for fuel rods, separating them from the coolant.

[16] "Frequently Asked Questions (FAQ) About Mixed Oxide Fuel," US Nuclear Regulatory Commission (NRC), August 16, 2010, http://www.nrc.gov/materials/fuel-cycle-fac/mox/faq.html (accessed September 30, 2010); "Fuel Fabrication," US Nuclear Regulatory Commission (NRC), October 29, 2009 http://www.nrc.gov/materials/fuel-cycle-fac/fuel-fab.html (accessed September 30, 2010); Nuclear Energy Institute (NEI), "2000: An Eventful Nuclear Year," *Nuclear Energy Insight* (January 2010): 1-8.

[17] "Fuel Fabrication," World Nuclear Association (WNA), http://www.world-nuclear.org/how/fuelfabrication.html (accessed September 29, 2010).

Stage 5: The Nuclear Reactor

Heavy-water reactor (HWR)

Heavy-water reactors (HWRs) use heavy water (deuterium oxide, D0) as a neutron moderator. Neutrons in a nuclear reactor that uses uranium must be slowed down so that they are more likely to split other atoms and get more neutrons released to split other atoms. Light water can be used, as in a light-water reactor, but since it absorbs neutrons the uranium must be enriched for criticality to be possible. The most common pressurized heavy water reactor is the CANDU reactor.

Heavy water is water in which deuterium, a heavy isotope of hydrogen, takes the place of hydrogen. It is chemically identical to ordinary water, except that the hydrogen atoms in the molecule are the deuterium isotopes. It is an excellent moderator for nuclear reactions because it slows down the fast neutrons produced in a nuclear fission reaction, increasing the likelihood that the neutrons will collide with heavy nuclei to cause further fission.

Opponents of HWRs argue that this technology presents a greater risk of nuclear proliferation. While allowing the use of natural uranium as a fuel without the need for its enrichment (thereby offering a greater degree of energy independence), HWRs produce more plutonium and tritium as a by-product of normal use than light-water reactors. Both plutonium and tritium are hazardous radioactive substances, used in the production of modern nuclear weapons and neutron bombs as well as in the primary stages of thermonuclear weapons. India produced its plutonium for Operation Smiling Buddha, its first nuclear weapon test from plutonium extracted from a heavy-water research reactor known as "CIRUS." Heavy-water reactors require a set of safeguards to prevent their exploitation in such a fashion.

HWRs are now a very significant part of world reactor installations, second to light-water reactor facilities. The main reason is that despite proliferation concerns, they provide flexibility with regard to fuel cycle operation and can burn the recycled fuel from light-water reactors, which enables to extend resources and reduce spent fuel storage.

CANDU Reactor

The CANada Deuterium Uranium (CANDU) reactor is a Canadian-invented, pressurized heavy-water reactor. The reactors are used in nuclear power plants to produce nuclear power from nuclear fuel. CANDU reactors were developed initially in the late 1950s and 1960s through a partnership between Atomic Energy of Canada Limited (AECL), the Hydro-Electric Power Commission of Ontario (renamed Ontario Hydro in 1974, and, since 1999, known as Ontario Power Generation), Canadian General Electric (now known as GE Canada), and other private industry participants.

The acronym "CANDU," is a reference to its deuterium-oxide (heavy water) moderator and its use of uranium fuel (originally, natural uranium). All current power reactors in Canada are of the CANDU type. Canada markets this power reactor abroad. In December 2009, the Canadian Federal Government announced that it would be seeking private investors for a partial sell-off of its CANDU division.

Because of its relative simplicity, it is in vogue in developing countries. New designs are being developed in Canada and to a lesser extent in India. The core of the nuclear steam supply system of CANDU 6 power plant is a large cylindrical vessel. This vessel, called "the calandria," is filled with cool, low-pressure D2O. The vessel houses 380 horizontal tubes that are loaded with natural uranium fuel bundles. With the uranium fuel surrounded by heavy water, a chain reaction fission takes place, which releases energy (heat). That heat is transferred to a second heavy-water system pumped at high pressure through the tubes to steam generators – the heat is then transferred to ordinary water that boils to become the steam that drives the turbine generator.

Light Water Reactor (LWR)[18]

There are six components to the LWR structure: condenser, feed water pipe, control rod structure, reactor core, steam turbine, and generator. Light water is added to the feed pipe it travels to the secondary loop, which connects to the primary loop. Afterward it is filtered to the reactor core where chain reaction occurs, and then it moves to the secondary loop where it is cooled.

Water (H_2O) instead of Heavy water (D_2O), Deuterium, is used to cool the fuel rods to produce steam. The steam travels to a turbine that propels a generator, creating electricity. The remaining steam and water is transferred to the condenser where it is filtered and fed back into the feeding tube. The process still can create Pu-239 from uranium; however, it is more difficult to extract weapons-grade Pu-239 from Pu-240 LWR spent fuel, because it is combined with various other actinides. It is more difficult to develop weapon-usable plutonium from LWR nuclear waste. There are two types of light-water reactors; a pressurized water reactor (PWR) and a boiling water reactor (BWR).

Pressurized Water Reactor (PWR) [19]

Pressurized water reactors (PWRs) constitute a majority of Western nuclear power plants. In a PWR the primary coolant is pumped under high pressure to the reactor core. The heated water then transfers thermal energy to a steam generator. In contrast to a boiling-water reactor, pressure in the primary coolant loop prevents the water from boiling within the reactor. The coolant and the reactor are separate from the turbine, enclosed in a

[18] "How a Pressurized Water Nuclear Reactor Works," Prairie Island Coalition, http://www.no-nukes.org/prairieisland/howitworks.html (accessed September 29, 2010); "Light Water Nuclear Reactors," http://hyperphysics.phy-astr.gsu.edu/hbase/nucene/ligwat.html (accessed Sept. 29, 2010).
[19] Ibid.

primary loop. If there is a reactor leak, then the coolant and the radioactive contaminants will remain separate, and not travel to the turbine or generator. PWRs function at much higher temperatures, and are harder to develop.

PWRs were originally designed to serve as nuclear submarine power plants and were used in the original design of the second commercial power plant at Shippingport Atomic Power Station. PWRs are considered Generation II reactors. VVER is the Russian term for Russian-designed PWRs.

Boiling Water Reactor (BWR)[20]

The BWR uses demineralized water (light water) as a coolant and neutron moderator. Heat is produced by nuclear fission in the reactor core, and this causes the cooling water to boil, producing steam. The steam is directly used to drive a turbine, after which it is cooled in a condenser and converted back to liquid water. This water is then returned to the reactor core, completing the loop. The cooling water is maintained at about 75 atm (7.6 MPa, 1000–1100 psi) so that it boils in the core at about 285 °C (550 °F). In comparison, there is no significant boiling in a PWR because of the high pressure maintained in its primary loop – approximately 158 atm (16 MPa, 2300 psi).

The BWR is the second-most common type of electricity-generating nuclear reactor after the pressurized water reactor (PWR). The BWR was developed by the Idaho National Laboratory and General Electric in the mid-1950s. General Electric specializes in the design and construction of this type of reactor.

Fast Breeder Reactor (FBR)

The fast breeder reactor (FBR) is a nuclear reactor designed to produce more fuel than it consumes. FBR irradiates neutrons from a reactor at a high speed to depleted uranium (U-238) and converts it into Pu-239, which is more fissionable. FBR technology is expected to offer better usage efficiency of uranium sources. FBR is typically designed to have breeding ratio of 1.2 to 1.5.[21]

Countries such as Russia, France, Japan, and India have been developing FBR (US, UK and Germany had FBR programs as well, but abandoned them); however, none has succeeded in commercialization of FBR. It is costly to build and operate FBR, and it is not yet commercially competitive against light-water reactors. Since a nuclear power reactor generates intense heat, it needs "coolant" to remove heat from the reactors. Most reactors such as light-water reactors and boiling water reactors use water as a coolant. FBR uses liquid sodium as a coolant. However, liquid sodium is chemically-active and initiates severe chemical reactions when exposed to water and oxygen. In 1995, Japanese FBR "Monju" had a serious accident when leaked sodium reacted with oxygen and

[20] Ibid.
[21] "Fast Neutron Reactors," World Nuclear Association, http://www.world-nuclear.org/info/inf98.html (accessed August 5, 2020).

moisture in the air, and caused a fire. It took 15 years for Monju to restart performance testing.

FBR uses and produces plutonium, which raises proliferation concerns. In 1974, India used plutonium separated from its breeder reactor to make a "peaceful" nuclear explosion. France used its breeder reactor to produce weapon-grade plutonium.[22]

Liquid Metal Fast Breeder Reactor[23]

Internationally, the liquid-metal fast breeder reactor is considered the most promising application of recycling. It has a radically different design that has been demonstrated to be technically feasible but is not available commercially. "*Liquid metal"* refers to the coolant, usually a molten alloy of sodium and potassium. "*Fast*" refers to the speed of the neutrons in the reactor core. Since fast reactors do not incorporate a moderator, the neutrons are not slowed much from their speed at birth in the fission process. "*Breeder*" refers to the fact that more fissile material is bred from fertile material than is consumed by fission. Often, this type of reactor is said to produce more fuel than it consumes. However, its essential characteristic is that it consumes much less uranium than current reactors. This approach extends the availability of known uranium reserves to hundreds of years.

Liquid-metal fast breeder reactors usually use a mixed oxide fuel core of up to 20 percent plutonium dioxide (PuO_2) and at least 80 percent uranium dioxide (UO_2). Another fuel option is metal alloys, typically a blend of uranium, plutonium, and zirconium. The plutonium used can be supplied by reprocessing reactor outputs or "off the shelf" from dismantled nuclear weapons.

Graphic 6: FBR "Monju," The Kansai Electric Co., Inc., http://www.kepco.co.jp/plu/18.html

[22] Thomas B. Cochran, Harold A. Feiveson, et.al. "History and status of fast breeder reactor programs worldwide," International Panel on Fissile Materials, February 2010, 1-16.

[23] J.A.L. Robertson, "Decide the Nuclear Issues for Yourself: Nuclear Need not to be Unclear," http://www.magma.ca/~jalrober/Chapter3.htm (accessed September 8, 2010). For more details of the current status of technological feasibility, see Eduard Khodarew, "Liquid Metal Fast Breed Reactors," *IAEA Bulletin*, Vol 20, http://www.iaea.org/Publications/Magazines/Bulletin/Bull206/20604782938.pdf (accessed September 8, 2010).

Stage 6: Spent Fuel Storage

The high-level waste (HLW) produced in the reactor core (spent fuel) is highly radioactive and thermally hot. This spent fuel requires initial treatment and management to successfully isolate it from interacting with the environment. Long-term storage of radioactive waste involves the stabilization of waste into a form that will neither react nor degrade for extended periods of time and a long-term management strategy involving permanent storage or disposal. There are currently no long-term nuclear waste disposal solutions that can safely manage this radioactive waste until it decays (due to the length of the time frames involved).[24] The safe development of interim storage solutions is of particular importance given the absence of viable long-term options and the security, environmental, and proliferation risks posed by that high-level waste.

Spent Fuel Management

Spent fuel management refers to the final phases of the nuclear fuel cycle where the radioactive waste from the reactors is either stored and/or recycled. In an open or a "once-through" fuel cycle, the spent fuel is discharged from the power reactor, placed in interim storage for cooling purposes and then disposed of in a repository. In a closed fuel cycle, the spent fuel is reprocessed or recycled after it is discharged from the power reactor to be enriched and reused in the power reactor.[25]

A summary of the amounts of radioactive wastes and management approaches for most developed countries are presented and reviewed periodically as part of the IAEA Joint Convention on Safety of Spent Fuel Management and the Safety of Radioactive Waste Management.

Interim Storage Solutions

In the place of long-term options or recycling, nuclear power plants that do not reprocess spent fuel use spent fuel pools to store the waste at the reactor sites. When nuclear reactors were developed, these pools were designed as a temporary storage option, but they have been relied upon to provide interim storage pending a permanent waste repository. Many of the spent fuel pools at commercial nuclear power plants are nearing capacity. To mitigate this problem, dry cask storage was developed at both reactor sites and independent spent fuel storage installations (ISFSI) to free up additional space in the pools for storing spent fuel newly removed from reactors.

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[24] "Strategic Cooperation Sets the Scene for Geological Disposal of Nuclear Waste in Europe," European Commission, http://ec.europa.eu/dgs/jrc/downloads/jrc_aaas_20100219_newsrelease_geological_disposal_en.pdf (accessed September 30, 2010).

[25] Dyck, Peter and Martin J. Crijins, "Rising Needs: Management of Spent fuel at Nuclear Power Plants," *IAEA Bulletin*, http://www.iaea.org/Publications/Magazines/Bulletin/Bull401/article6.html (accessed September 30, 2010).

This is a policy area that requires a comprehensive assessment of a range of factors (technical, political, strategic, security, ethical, financial, environmental, and geological). Spent fuel must be managed in a way that allows for appropriate long-term storage, but is stable and secure in the short to mid-term.

Spent Fuel Pools

Most nuclear power plants are designed with small storage pools for spent fuel. Spent fuel is contained in rods which are bundled into fuel assemblies, and are removed from the reactor core after they lose efficiency. Between a third and a quarter of the fuel rods are replaced every 12 to 18 months. A typical reactor will generate 20 to 30 tons of high-level nuclear waste annually (equivalent to the cargo area of a small commercial truck).

The fuel assemblies are held under water to reduce radiation levels and to cool (as they continue to produce decay heat) for a period of 10-20 years. Most spent fuel remains stored in these pools at individual reactor sites. The spent fuel rods are arranged in the pool on metal racks to avoid criticality (a chain reaction) and the water temperature is monitored and cooled by a heat exchanger, with back-up cooling solutions for emergencies. Due the absence of viable long-term storage options the pools (in the US) have been re-racked to allow for the storage of more fuel rods in each pool. These reactors were designed before the waste or reprocessing solutions and the pools themselves were not designed to act as interim solutions. The US Nuclear Regulatory Commission (NRC) suggested that these pools will near capacity by 2015.

These pools pose a number of risks, particularly as they reach capacity. If the fuel pool water boils or drains away, the spent fuel assemblies will overheat, causing them to melt or catch on fire. These pools pose a risk if subject to sabotage, accident, or attack as the high temperature fire could release large quantities of radioactive material into the environment. There is also no standard design for these pools and they are often in less robust structures than reactor containment vessels. Critics argue that the pools were not designed to serve as storage solutions.

Dry Cask Storage

Dry cask storage was introduced in 1986 as an alternative storage solution to pools at nuclear reactors as they reach capacity. After the fuel has been cooled sufficiently it can be removed from the spent fuel pool and loaded into dry casks for storage, freeing up space in the pool for spent fuel newly removed from reactors. Storing nuclear fuel in dry casks involves surrounding the fuel with inert gas inside steel cylinders that are either welded or bolted closed. The steel cylinder provides a leak-tight containment of the spent fuel. Each cylinder is surrounded by additional steel, concrete, or other material to provide radiation shielding to workers and members of the public. Some designs are placed inside a concrete vault to provide radiation shielding.

Some of these casks have been designed for both storage and transportation and are commonly referred to as CASTOR containers, which is an acronym for "cask for storage and transport of radioactive material."

Spent fuel is currently stored in dry cask systems at a growing number of power plant sites and at independent facilities. Dry spent fuel storage in casks is considered to be safe and environmentally sound. Over the last 20 years, there have been no radiation releases which have affected the public, no radioactive contamination, and no known or suspected attempts to sabotage spent fuel casks or Independent Spent Fuel Storage Installations (ISFSIs). Dry cask storage systems are designed to resist floods, tornadoes, projectiles, temperature extremes, and other unusual scenarios.

The US Nuclear Regulatory Commission (NRC) has performed a generic environmental impact study for ISFSIs. It states that spent fuel can be stored safely and without significant environmental impacts for at least 30 years beyond the licensed reactor life. [26]

Near Surface Storage

Near Surface Storage is a disposal option typically used for Low- and Intermediate-Level Waste (LILW) with short half-lives (up to about 30 years). The disposal facilities are either at ground level or a few meters below the surface. Thus, these facilities will be affected by long-term climate changes (such as glaciations). These changes should be taken into account when storing waste as they can cause damage and disruption to the facilities. [27]

Near-surface disposal facilities are in operation in:

- UK: Low Level Waste Repository at Drigg in Cumbria operated by UK Nuclear Waste Management Ltd (a consortium led by Washington Group International with Studsvik UK, Serco and Areva) on behalf of the Nuclear Decommissioning Authority.
- Spain: El Cabril low – and intermediate-level radioactive waste disposal facility operated by ENRESA.
- France: Centre de l'Aube operated by Andra.
- Japan: Low-Level Radioactive Waste Disposal Center at Rokkasho-Mura operated by Japan Nuclear Fuel Limited.
- USA: three low-level waste disposal facilities at: Barnwell, South Carolina – operated by EnergySolutions; Richland, Washington – operated by American Ecology Corporation (formerly U.S. Ecology); and Clive, Utah – operated by EnergySolutions.

[26] The federal NRC licenses the storage casks and has concluded that they can be safely used for as long as a century, although it requires re-licensing every 20 years. http://www.safesecurevital.org/dry-cask-storage-faqs/ (accessed September 30, 2010).

[27] "Storage and Disposal Options," World Nuclear Association, http://www.world-nuclear.org/info/inf04ap2.html (accessed July 27, 2010).

Near-surface disposal facilities in caverns below ground level are in operation in:

- Sweden: the SFR final repository for short-lived radioactive waste at Forsmark, where the facility is 50m under the Baltic seabed – operated by the Swedish Nuclear Fuel and Waste Management Company (SKB).
- Finland: Olkiluoto and Loviisa power stations where the depths of the facilities are each about 100 meters.

Deep Geological Deposits

Deep geological disposal is a spent fuel repository typically used for High-Level Waste (HLW) with long half-lives (thousands of years). There are several types of repositories including those made of strong fractured rocks, layered salt strata, and clay. These repositories are comprised of mined tunnels and caverns into rock units that are reasonably stable and without major groundwater flow at depths of between 250m and 1000m. In some cases (e.g., wet rock) the waste containers are surrounded by cement or clay (usually bentonite) to provide another barrier (called buffer or backfill).

Deep geological disposal remains the preferred option for waste management of long-lived radioactive waste in several countries, including Argentina, Australia, Belgium, Czech Republic, Finland, Japan, Netherlands, Republic of Korea, Russia, Spain, Sweden, Switzerland, and the US.[28]

Radiation

Radiation is a form of energy transfer that occurs through the transmission of waves or particles of energy.[29] Exposure to radiation occurs on a daily basis, from outer space (cosmic rays), radioactive elements in the earth, man-made sources (X-rays, nuclear diagnostics and radiation therapy, smoke detectors) and even from our own bodies.[30]

There are two main types of radiation – ionizing and non-ionizing. In the nuclear field, the term 'radiation' generally refers to ionizing radiation.[31] This category can be further broken down into three kinds of ionizing radiation – alpha, beta, and gamma.

Alpha radiation occurs when heavy, positively charged particles are emitted by atoms of elements such as uranium and plutonium. Alpha particles cannot penetrate far inside the body: A sheet of paper or the surface layer of skin provides an adequate barrier for the

[28] Waste Management and Disposal," World Nuclear Association, http://www.world-nuclear.org/info/inf04.html (accessed July 27, 2010).
[29] *Uranium and other radioactive elements*, (Atlantic Publishing Group: 1996), 54.
[30] Henry N. Wagner and Linda E. Ketchum, *Living With Radiation* (Johns Hopkins University Press: Baltimore, Maryland and London, 1989) 31; "Sources and Effects of Ionizing Radiation," United Nations Scientific Committee on Effects of Atomic Radiation (UNSCEAR) (United Nations: New York, 1977), 15.
[31] Ionizing radiation is that which is capable of producing ions in the air.

body. However, if alpha-emitting material, such as radioactive dust, is ingested or inhaled it may cause biological damage to DNA, which can cause the mutation of cells.

Beta radiation consists of electrons that are able to penetrate more deeply than alpha particles, and can penetrate between 2-3 centimetres of tissue. However, beta particles can be blocked by aluminium only a few millimetres thick.[32]

Gamma radiation can pass through the human body. Similar to X-rays and radio waves, gamma rays are electromagnetic. Blocking gamma rays requires a thick concrete or lead wall.

Not all radioactive elements emit alpha and beta particles and gamma rays simultaneously. Some emit just alpha particles; others both alpha and beta particles; others beta particles and gamma rays; and yet others just gamma rays.[33]

[32] *Uranium and Other Radioactive Elements*, (Atlantic Publishing Group: 1996), 42.
[33] L.A. Redman, *Nuclear energy*, (Oxford University Press: London, 1963), 23http://www.iaea.org/Publications/Factsheets/English/radlife.html (accessed August 21, 2010).

Stage 7: Reprocessing / Recycling

PUREX Reprocessing

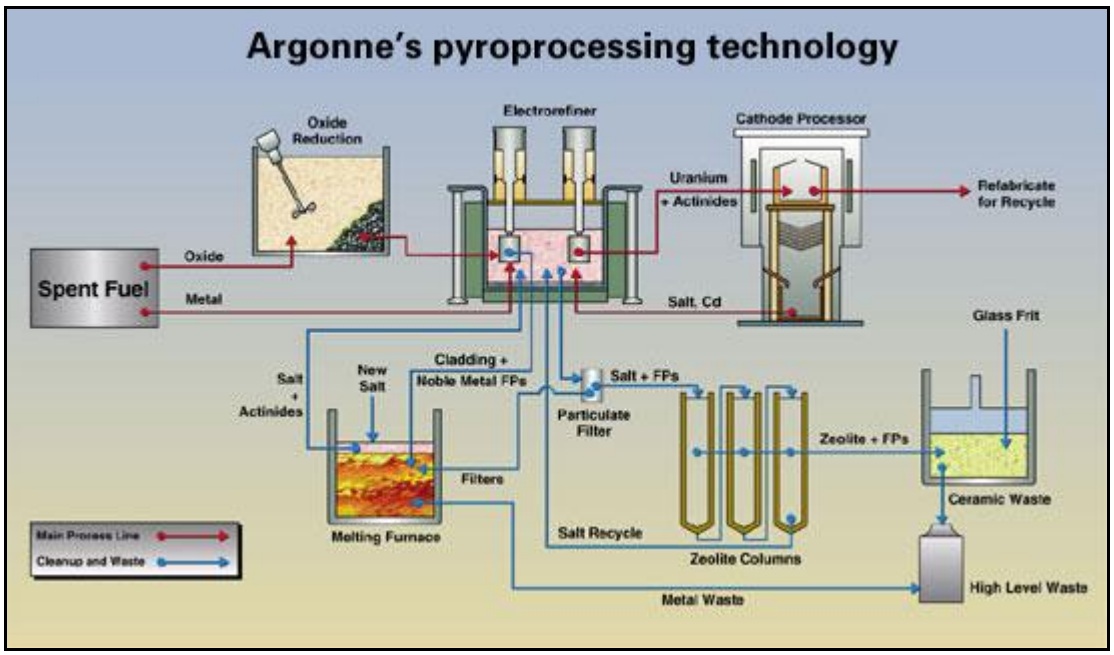
PUREX stands for Plutonium Uranium Extraction. The process begins by dissolving irradiated fuel in aqueous nitric acid. The nitric acid removes a sufficient amount of solids from the irradiated fuel. The fuel is then mixed with a solvent that is 30 percent tributyl phosphate (TBP) and 70 percent kerosene to extract the uranium and plutonium. This process is repeated until the appropriate levels of actinides are removed from the fuel leaving only uranium and plutonium. The process is described as a liquid-liquid extraction process.

The US Department of Energy under the Global Nuclear Energy Program is developing uranium extraction (UREX +) which is designed to recycle the uranium and to recover residual plutonium and other transuranic elements. Transuranic elements are artificially developed, radioactive elements with an atomic number 92-118. The UREX+ process separates a mixed uranium-plutonium stream from a transuranic stream. This process is proliferation resistant, because a nation would need to separate the fissile uranium. However, there are fewer elements to separate from the mixture. Other processes such as UREX +1a process separate uranium, plutonium-neptunium mixture for MOX fuel. These are fission products that require long-term storage such as transuranic elements americium and curium. The plutonium transuranic compound is then burned in a fast breeder reactor, leaving only plutonium. UREX +1a combines plutonium with three minor actinides (neptunium (Np), americium (Am), and curium (Cm). However, many of the actinides combined with Pu require separate fuel fabrication for it to be reused in a nuclear reactor. UREX+3 is another process that is closer to MOX fuel since it combines Pu with Np. However, it is not as proliferation resistant as UREX+1a because the plutonium is mixed with only one other actinide. PUREX is useful for developing weapons-grade plutonium. UREX solvent extraction is a useful for extracting and recycling fissile plutonium, and uranium. UREX +1a, UREX+ and UREX+3 are all proliferation resistant, with UREX +1a being the most proliferation resistant and useful for recycling uranium and plutonium for peaceful purposes. Processes such as UREX+ would be most susceptible to proliferation because it has fewer elements to separate from the uranium.

Pyroprocessing

Unlike traditional forms of reprocessing that separate uranium and produce plutonium to be recycled back into reactors, pyroprocessing is a form of "electrorefining." Electrorefining removes uranium, plutonium, and the other actinides (highly radioactive elements with long half-lives) from the spent fuel, while keeping them mixed together so the plutonium cannot be used directly in weapons. Because the fuel contains a large percentage of actinides, the fuel is useable in reactors but nearly useless for making nuclear weapons. This is in contrast to the PUREX process, which separates the actinides from the uranium and plutonium and creates more dangerous nuclear waste. Because

pyroprocessing is more compact than aqueous processes that require spent fuel to be transported, pyroprocessing can be done onsite. This may eliminate the need for the transportation and security of the hazardous waste.



Graphic 7: "Argonne's pyroprocessing technology," http://www.anl.gov/Media_Center/Frontiers/2002/d1ee4.html

Development of this process is widely discussed in the context of the US-South Korean nuclear cooperation that expires in March 2014.

With US assistance through the International Nuclear Energy Research Initiative (I-NERI) program, the Korea Atomic Energy Research Institute (KAERI) built the Advanced Spent Fuel Conditioning Process Facility (ACPF) at the Institute. KAERI hopes the project will be expanded to engineering scale by 2012, leading to the first stage of a Korea Advanced Pyroprocessing Facility (KAPF) starting in 2016 and becoming a commercial-scale demonstration plant in 2025. South Korea has declined an approach from China to cooperate on electrolytic reprocessing, and it has been rebuffed by Japan's Central Research Institute of Electric Power Industry (CRIEPI).

The Russian Institute of Atomic Reactors (RIAR) at Dimitrovgrad has developed a pilot scale pyroprocessing demonstration facility for fast reactor fuel. GE Hitachi is also designing an Advanced Recycling Centre (ARC) that integrates electrometallurgical processing with its PRISM fast reactors.[34]

[34] "Argonne's pyroprocessing technology," Argonne National Laboratory, http://www.anl.gov/Media_Center/Frontiers/2002/d1ee4.html (accessed July 27, 2010); "Processing of Used Nuclear Fuel," World Nuclear Association, http://www.world-nuclear.org/info/inf69.html#Electrometallurgical (accessed July 27, 2010).

Stage 8: Vitrification

Vitrification is a process that permanently traps harmful chemicals in a solid block of glass-like material. This keeps them from leaving the site. Vitrification can be done in place or above ground. In treating nuclear waste, vitrification means turning radioactive waste into glass. A treatment plant takes nuclear waste, primarily stored in underground tanks, and combines it with molten glass.[35] The glass is then sealed in steel containers. The waste should remain stable as the radioactivity dissipates.

Stage 9: Final Disposal

Final disposal

Final disposal is the last stage of the nuclear fuel cycle. Intensely radioactive spent fuel assemblies that contain a lot of heat taken from the reactor, after being stored in special bonds for long periods to cool, will be either reprocessed or sent to direct disposal.[36] Spent fuel sent to final disposal is enclosed in very strong, metallic dry casks, which are filled with inert gas and sealed to shield the fuel's remaining radiation.[37] If the used fuel is reprocessed, after reprocessing unrecyclable high-level waste is heated at high temperature to produce a dry powder which is then immobilized by incorporating into refractory glass. The glass is moved to dry storage canisters made of corrosion-resistant metals such as stainless steel.[38]

These spent fuel/high-level waste containers are projected to be buried deep underground in stable rock structures, or repositories, such as granite, volcanic tuff, salt, or shale.[39] This final stage has not yet taken place, however, due to environmental as well as social, and political concerns. Persistent anxieties over radioactive waste leaking from burial sites, escaping into the environment and contaminating, for example, drinking water have led to public discomfort with disposal proposals in many countries, which prompts politicians to opt for reprocessing options,[40] Yet it may be more cost-effective for some

[35] Nuclear and Indigenous Items of Interest http://gregornot.wordpress.com/2008/07/22/what-is-vitrification/ (accessed September 7, 2010).

[36] "The nuclear fuel cycle," World Nuclear Association (WNA), http://www.world-nuclear.org/education/nfc.htm (accessed July 25, 2010).

[37] Eugene E. Voiland, "Disposal of high level nuclear waste," Center for Reactor Information (CFRI), May 2002, http://www.sustainablenuclear.org/PADs/pad0205voiland.html (accessed July 25, 2010); Sarah M. Don, "Nuclear waste disposal – Issues and Impacts on Industry and Society," Australia, October 24, 2008, http://www.scribd.com/doc/11337859/Nuclear-Waste-Disposal (accessed August 26, 2010).

[38] "The nuclear fuel cycle," World Nuclear Association (WNA), http://www.world-nuclear.org/education/nfc.htm (accessed July 25, 2010)

[39] Ibid.

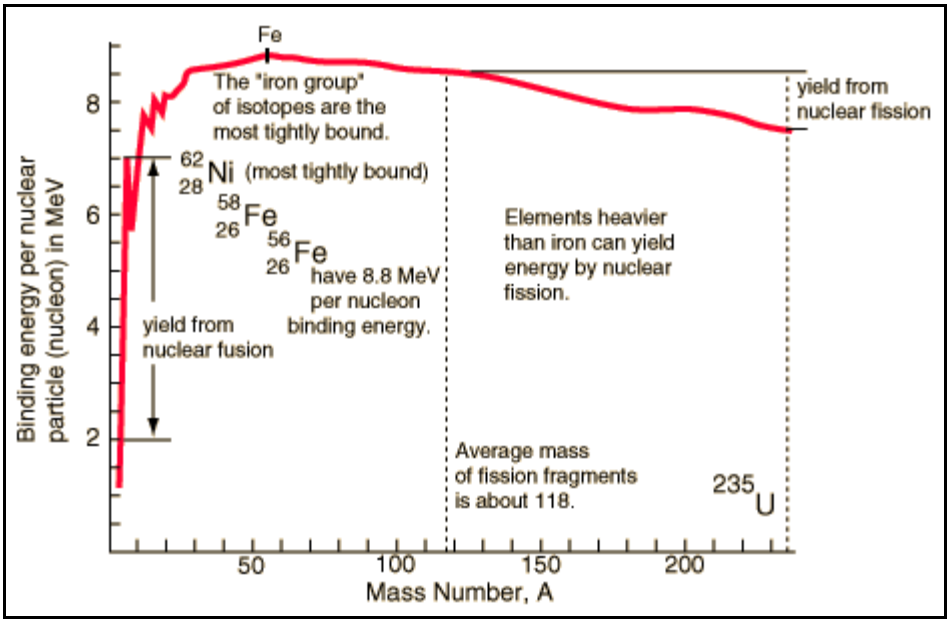
[40] "Waste from nuclear power," nuclearinfo.net, http://nuclearinfo.net/Nuclearpower (accessed Aug. 26, 2010); Sarah M. Don, "Nuclear waste disposal – Issues and impacts on Industry and Society," Australia, Oct. 24, 2008, http://www.scribd.com/doc/11337859/Nuclear-Waste-Disposal (accessed Aug. 26, 2010).

countries to dispose of all nuclear wastes than to reprocess and recycle them,[41] which may increase proliferation risks.

[41]Sarah M. Don, "Nuclear waste disposal – Issues and impacts on Industry and Society," Australia, October 24, 2008, http://www.scribd.com/doc/11337859/Nuclear-Waste-Disposal (accessed August 26, 2010).

Nuclear Weapons

Two types of nuclear weapons exist: those that produce energy through nuclear fission reactions alone (atomic bomb, fission bomb or A-bomb), and those that produce a large amount of energy through nuclear fusion, such as the hydrogen bomb. Nuclear weapons that use fusion reactions can be thousand times more powerful than those that use fission alone. As shown below (to the right), the energy released by fusion is three to four times greater than the energy released by fission. This is because the amount of mass transformed into energy is that much greater in a fusion reaction than in a fission reaction. In addition, because the elements used in fusion are so much smaller than those used in fission (by a factor of ca 200!), the energy density of the fuel is even higher than depicted in the chart below:



Graphic 6: graph of energy yield from fusion and fission, "Nuclear Binding Energy," http://hyperphysics.phy-astr.gsu.edu/hbase/nucene/nucbin.html

Atomic Bomb[42]

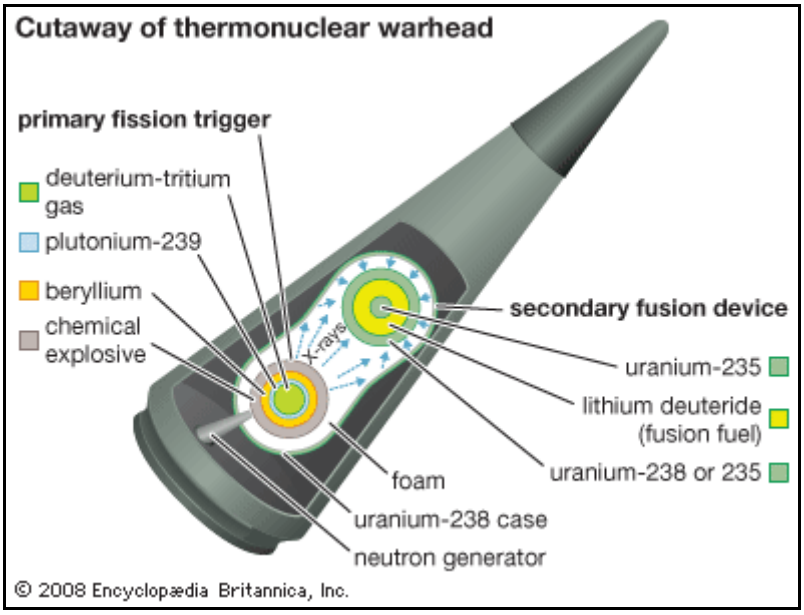
"Atomic bomb" describes a type of nuclear weapon whose primary source of power comes from the fission of highly enriched uranium or plutonium. This differs from a hydrogen bomb, which gains its explosive power from nuclear fusion and is much more powerful. The world's first atomic bomb was tested by the US in 1946 in New Mexico, and was the culmination of the secretive Manhattan Project, led by J. Robert Oppenheimer. An atomic bomb was dropped on Hiroshima and Nagasaki in 1945.[43]

[42] Joseph Cirincione, *Bomb Scare: The History and Future of Nuclear Weapons* (New York: Columbia University Press, 2007): 209 and 212.

[43] Although both the bombs that were dropped in Hiroshima and Nagasaki were atomic bombs, one was a uranium-238 gun type, and the other a plutonium implosion-type bomb. See "Hiroshima and Nagasaki

Thermonuclear Weapons[44]

Often called "hydrogen bombs" or "H-bombs" because of the secondary, fusion reaction between deuterium and tritium (both isotopes of hydrogen), thermonuclear weapons use the combined energy created by dual nuclear fission and nuclear fusion reactions to create a destructive force much more powerful than the standard atomic (fission) device. A three-stage reaction is necessary to create a full detonation, but each stage occurs almost simultaneously. First, a chemical explosive that surrounds a sphere of Pu is detonated. The force of this detonation then causes a fission reaction, which kick-starts the final fusion reaction between hydrogen isotopes.



Graphic 7: Cut out of a thermonuclear warhead, **Encyclopædia Britannica Online,** http://www.britannica.com/EBchecked/topic-art/619171/110972/The-blast-from-a-primary-fission-component-triggers-a-secondary

Remembered," National Science Digital Library http://www.hiroshima-remembered.com/ (accessed September 30 2010).

[44] Union of Concerned Scientists, "How it Works: Thermonuclear Weapons," *Catalyst* Vol. 6 (Spring 2007): http://www.ucsusa.org/publications/catalyst/thermonuclear-weapons.html (accessed September 30, 2010); Joseph Cirincione, *Bomb Scare: The History and Future of Nuclear Weapons* (New York: Columbia University Press, 2007), 212; Frank Barnaby, *How Nuclear Weapons Spread: Nuclear Proliferation in the 1990s* (London: Routledge, 2004), 35 and 72.

Neutron Bomb[45]

Neutron bombs are a type of thermonuclear weapon that uses fusion to enhance the radiation output beyond which standard atomic devices are capable. In the fusion reaction, neutrons are intentionally allowed to escape through the use of X-ray mirrors and an atomically inert shell casing, such as chromium or nickel.

Neutron bombs are often considered to be "small" bombs because the energy yield can be as little as half that of a conventional device. However, their radiation output is only slightly less, with a yield in the tens or hundreds of kilotons range. What makes neutron bombs different from other nuclear devices is that their lethality stems from the radiation they emit, as they leave most physical structures intact.

Tritium

Tritium (T or 3H) is the only radioactive isotope of hydrogen. The nucleus of a tritium atom consists of a proton and two neutrons. The most common forms of tritium are tritium gas and tritium oxide (also called tritiated water).

Tritium is generated both by natural and artificial processes. It is naturally produced in the atmosphere and incorporated into water (liquid and vapor), falling on Earth as rain, though in extremely small quantities. Given that very little tritium is present in nature, it has to be produced artificially to be used on a practical scale. It is made in production nuclear reactors, produced by neutron absorption of a lithium-6 atom, which form a lithium-7 atom of three protons and four neutrons, which in turn splits to form an atom of tritium (one proton and two neutrons) and an atom of helium-4 (two protons and two neutrons).

Tritium is used as a component in nuclear weapons to boost the yield of fission and fusion warheads, particularly fusion warheads (large quantities of tritium are necessary to maintain a nuclear arsenal). It is also produced commercially in nuclear reactors and fuel reprocessing plants, as well as in life science, chemical, and environment studies.

The most worrying form of tritium for human beings and the environment is tritium oxide, which cannot be distinguished from normal water. It presents a danger only if it is taken into the body because tritium undergoes radioactive decay by emitting a very weak beta particle.

Significant quantities of tritium were dispersed in the atmosphere when nuclear tests were conducted above the ground, in the 1950s and 1960s. Since then, quantities have

[45] Anne Marie Helmenstine, "What is a neutron bomb?" About.com: Chemistry, http://chemistry.about.com/od/chemistryfaqs/f/neutronbomb.htm (accessed Sept. 30, 2010); "The Neutron Bomb," Atomic Archive, http://www.atomicarchive.com/Fusion/Fusion5.shtml (accessed Sept. 30, 2010).

decreased but remain present. Today, the only sources of tritium are commercial and research nuclear reactors and weapon production plants.[46]

Nuclear Fallout[47]

Nuclear fallout occurs after a nuclear explosion, when dust particles and other debris swept upward by the explosion are contaminated with nuclear radiation and then dispersed downwind. If the explosion occurs on/near the ground, it will likely create large particles made up of radioactive debris, dust, and soil particles. If the blast happens in the air where it is unable to suck dirt particles from the ground, lighter particles will be scattered. Eventually these radiation-contaminated materials "fall out" of the atmosphere to the earth, although the speeds and scopes of their landing will vary depending on the altitude of the explosion: large, heavy particles often fall quickly to the immediate area, whereas small, lighter particles may be carried much further away.

"Local fallouts" are defined as those occurring within 50 to 500 km from the detonation site, "regional fallout" 500-3,000 km and global fallout more than 3,000 km. The highest radiation exposures are usually in areas of local fallout, since radioactivity gradually decreases as the fallout cloud spreads over time to long distances.

As radioactive dust travels on wind currents, it contaminates the air, ground, and animal food chain. This is intensified by rainfall creating intense localized concentrations. The detrimental impacts on local populations' health are often tremendous.

[46] "Tritium Information Section," Idaho State University, http://www.physics.isu.edu/radinf/tritium.htm (accessed September 30, 2010); "Tritum (Hydrogen 3)," Argonne National Laboratory, EVS, *Human Health Fact Sheet* (August 2005), http://www.ead.anl.gov/pub/doc/tritium.pdf (accessed Sept. 30, 2010); "Tritum," US Environmental Protection Agency, http://www.epa.gov/rpdweb00/radionuclides/tritium.html (accessed Sept. 30, 2010).

[47] Steven Simon, André Bouville and Charles Land, "Fallout from nuclear weapons tests and cancer risks," American Scientist, 2006, http://www.americanscientist.org/issues/num2/2006/1/fallout-from-nuclear-weapons-tests-and-cancer-risks/1 (accessed July 25, 2010); Jake Moilanen, "Fallout," http://www-personal.umich.edu/~jmoilane/nuclear/Fallout.html (accessed July 25, 2010).

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