Appendix: Key Concepts and Vocabulary for Nuclear Energy

Power Plant

In most power plants around the world, heat, usually produced in the form of steam, is converted to electricity. The heat could come through the burning of coal or natural gas, in the case of fossil-fueled power plants, or the fission of uranium or plutonium nuclei. The rate of electrical power production in these power plants is usually measured in megawatts or millions of watts, and a typical large coal or nuclear power plant today produces electricity at a rate of about 1,000 megawatts. A much smaller physical unit, the kilowatt, is a thousand watts, and large household appliances use electricity at a rate of a few kilowatts when they are running. The reader will have heard about the "kilowatt-hour," which is the amount of electricity consumed when electricity is used for an hour at a rate of one kilowatt, or for two hours at a rate of half a kilowatt.

Nuclear Fission

Nuclear fission is the process by which the nucleus of a very heavy atom, such as uranium or plutonium, absorbs a neutron and splits into two lighter nuclei (called fission products), releasing additional energy (see Figure A.1). Neutrons are uncharged subatomic particles that are present alongside protons inside the atomic nucleus. Being uncharged, neutrons can approach the positively charged nucleus without being repelled, and that enables them to induce nuclear reactions such as fission.

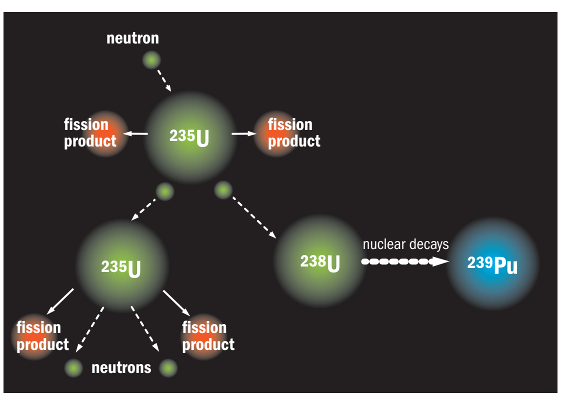

Figure A.1: A chain reaction produces steady power when the neutrons produced in every fission event produce exactly one further fission event. Plutonium is produced via neutrons that do not produce fission events.

The likelihood of fission depends on, among other things, the energy of the incoming neutron. Some nuclei can undergo fission even when hit by a low-energy neutron. Such elements are called fissile. The most important fissile nuclides are the uranium isotopes, uranium-235 and uranium-233, and the plutonium isotope, plutonium-239. Isotopes are variants of the same chemical element that have the same number of protons and electrons, but differ in the number of neutrons. Of these, only uranium-235 is found in nature, and it is found only in very low concentrations. Uranium in nature contains 0.7 percent uranium-235 and 99.3 percent uranium-238. This more abundant variety is an important example of a nucleus that can be split only by a high-energy neutron.

When a neutron comes close to any of these nuclei, it can not only fission them, it can also be absorbed by them. When a neutron is absorbed, the result is a different nucleus, often an unstable one that decays into yet another one. For example, after absorbing a neutron, uranium-238 becomes plutonium-239 through a series of nuclear decays. Analogously, when a neutron is absorbed by thorium-232, which is the only naturally occurring isotope of thorium, the result after two decays is uranium-233.

During fission, neutrons are released, typically two or three per fission. A chain reaction can result if enough of these neutrons can be absorbed by other heavy nuclei, causing these nuclei to split in turn, and so on. An important prerequisite is the presence of an adequate amount of fissile material in close physical proximity. In a nuclear reactor the chain reaction is tightly controlled, so that the number of fissions in one "generation" is exactly equal to that in the previous generation; the result is that energy (heat) is produced in a steady manner. By contrast, in a nuclear bomb, the fissions roughly double in each generation, leading to the release of a great deal of energy in a very short period of time, i.e., a nuclear explosion.

Nuclear Reactors

The region of the reactor where the self-sustaining chain reaction occurs and heat is produced from the slowing down of the fission products is called the nuclear core, or simply the core. A nuclear reactor includes not only the core, but also a heat exchanger where the heat from the coolant is transferred to either water (producing steam) or a gas. The steam or hot gas then drives a turbine that produces electricity. The size of a reactor can be quantified either by its rate of heat production in its core or the rate at which electricity is exported onto high-voltage transmission lines. Roughly, three units of heat produced at the core are converted into one unit of electricity and two units of degraded heat that is rejected to the local environment. In this distillate all sizes refer to its electricity production rate, measured in megawatts.

Small Modular Reactor

The International Atomic Energy Agency categorizes any reactor having an electrical output less than 300 megawatts as a small reactor. The term "small" is used in comparison with the average power delivered by currently operating reactors and the reactors under construction, which is just under 1,000 megawatts.

"Modular" means that the reactor is mostly constructed within a factory, with only limited assembly of factory-fabricated "modules" at the site of the power plant itself. Each module represents a portion of the finished plant. Depending on the reactor design, it may even be possible to manufacture the entire reactor in a factory and ship it to the reactor site. Modular construction has been increasingly incorporated into the building of nuclear reactors of all sizes, including large reactors. However, some components of a large reactor are so physically big and heavy that they cannot be transported and must be assembled on site. For example, the containment structure that envelops each of the AP1000 reactors being built in Georgia and South Carolina in the United States has four rings, the largest of which weighs over 650,000 kilograms. The word "modularity" also conveys the idea that rather than constructing one large reactor, the equivalent power output will be generated by multiple smaller reactors, thereby allowing greater tailoring of generation capacity to demand.

Reactor Types

Several nuclear reactor designs have been constructed, and many, many more have been proposed. These designs make very different choices for the kind of fuel used, the materials used to cool the reactor, and (if the neutrons are deliberately slowed down) for the materials used to slow down (or moderate) the neutrons.

Fuel

The fuel used in a reactor must contain one or more of the limited number of fissile isotopes. However, this fuel can take different forms—solid pellets of uranium oxide, a mixture of uranium and plutonium metals fashioned into thin rods, uranium tetrafluoride dissolved in a molten salt, thousands of small uranium oxide particles coated with multiple layers of different carbon compounds and embedded in graphite to form spheres roughly the size of a tennis ball, and so on.

Uranium Enrichment

Fuels also differ in the uranium-235 enrichment level in the uranium fuel, relative to its concentration in the uranium in the Earth's crust ("natural uranium"). Natural uranium consists of about 99.3 percent uranium-238 and 0.7 percent uranium-235 (the fissile isotope of uranium). The process of increasing the fraction of uranium-235 is called enrichment. Enrichment can be done by various technologies, including gaseous diffusion (the favored choice in the early days of nuclear energy) and gas centrifuges (today's technology of choice).

Uranium enrichment using centrifuge technology is achieved by feeding the uranium in the form of uranium hexafluoride gas to fast-spinning cylinders (up to 100,000 rotations per minute). Once inside the cylinder, the heavier uranium-238 nucleus drifts towards the outside wall of the cylinder, resulting in a gas enriched in uranium-235 at the center of the cylinder. The central gas molecules are then fed to the next centrifuge and so on, in a "cascade," until the desired level of enrichment is achieved.

Uranium in which the percentage of uranium-235 nuclei is not more than 20 percent is called low-enriched uranium, and when the percentage is more than 20 percent, it is called highly enriched uranium.

Coolant

A typical fission event produces about 200 million electron volts of energy. (Individual chemical reactions, such as the oxidation of a single molecule of hydrogen by oxygen, typically produce at most only a few electron volts of energy.) Over 80 percent of the energy released in fission is in the form of the kinetic energy of fast-moving fission products.

The kinetic energy turns into heat in the fuel as the fission fragments slow down, and this heat is then transferred into the reactor's coolant. Coolants come in three primary forms: gases (usually helium or carbon dioxide), liquids (usually ordinary water or heavy water), or molten metals (usually liquid sodium or lead).

Moderator

Reactors are distinguished by whether a neutron produced by fission mostly creates another fission before being slowed down, or this neutron is slowed down first and then produces another fission. Those reactors where the neutrons are not slowed down are called fast-neutron reactors, and those where the neutrons are slowed down are called thermal-neutron reactors. Fast neutrons travel at around 5 percent of the speed of light while thermal neutrons travel at around eight-millionths of the speed of light. The slowing down is achieved by collisions with light nuclei, such as hydrogen in water or carbon in graphite. When a neutron collides with a light nucleus it slows down more than when it hits a heavy one, because the light nucleus recoils more and carries away more of the neutron's original kinetic energy.

A chain reaction can be sustained with slow neutrons and natural uranium. If the moderator is water, it must be "heavy water," where the common form of hydrogen in water is replaced with a heavier form, deuterium. The hydrogen in ordinary water ("light-water") absorbs too many neutrons for a chain reaction to be sustained in natural uranium. In light-water reactors, the fuel must be enriched in the uranium-235 component in order to sustain a chain reaction. Typically, a light-water reactor requires 3 to 5 percent uranium-235.

Spent Fuel and Nuclear Waste

The radioactive products resulting from fission are not the only radioactive nuclei in a nuclear reactor. There are also structural materials made radioactive by neutron bombardment and radioactive "transuranic" elements (elements whose nuclei have more protons than uranium: neptunium, plutonium, americium, curium), produced when uranium-238 nuclei in the fuel absorb one or more neutrons followed by further decay processes. The fission products, the activated structural material, and the transuranic elements contain a mix of nuclei with all sorts of half-lives, from seconds to millions of years. Radioactive waste management is therefore a complex and highly regulated undertaking.

The irradiated fuel that is discharged from a nuclear reactor is called spent or used fuel. Spent fuel consists mainly of the uranium that has not undergone fission, fission products, and transuranic elements, notably the plutonium that has been produced by neutron absorption and subsequent transformation. Because of the high levels of heat and radiation emitted by spent fuel, upon discharge it is stored in pools of water. After several years, the spent-fuel elements can become cool enough to be taken out of water and stored in large air-cooled ceramic casks. This dry storage method has become more common in recent years as spent-fuel pools have been filling up, including at U.S. nuclear reactor sites.

The transuranic nucleus produced in greatest quantity in nuclear reactors is plutonium-239, created after a neutron is absorbed by uranium-238, the common uranium nucleus. Plutonium-239 can also be used in reactor fuel. This opens up the possibility of extracting a much greater amount of energy from the original uranium and providing fuel for more reactors from the finite amount of uranium ore available. The presence of plutonium in spent fuel has led some countries to adopt a chemical treatment method called "reprocessing" to separate out the plutonium.

Reprocessing can be done using a variety of chemical processes. The conventional method is called the Plutonium Uranium Redox EXtraction process, or PUREX for short, and was originally developed to separate out the plutonium for weapons. The process starts with chopping up the spent fuel and adding it to a hot nitric acid solution which dissolves the uranium, plutonium, and fission fragments but not the fuel's metallic alloy cladding. Later, the plutonium and uranium are separated from the fission products and transuranic elements. Other forms of reprocessing result in a product where the plutonium remains mixed with other transuranic elements.

Reprocessing creates the possibility of diverting the separated plutonium for use in nuclear weapons. Direct disposal is the alternative to all forms of reprocessing, including ones where plutonium is in a mixed form. Direct disposal of spent fuel requires permanent storage in a geological or other final repository. In this alternative the plutonium left in the spent fuel is relatively inaccessible, because the fission products provide a radioactive barrier to its removal. At present, wherever there is reprocessing, it only is done once, and spent fuel from reactors that have used reprocessed fuel is not reprocessed a second time. This is mainly due to technical challenges of reprocessing such spent fuel using currently deployed chemical processes.

Nuclear Weapons

Nuclear weapons are either pure fission explosives, such as the Hiroshima and Nagasaki bombs, or two-stage thermonuclear weapons with a fission explosive as the first stage and a fusion explosive as the second stage. The former are easier to produce. In a fission weapon, a sufficient quantity of fissile material has to be brought into close proximity so that it can sustain a chain reaction for a brief period. The amount of fissile material required depends on a number of design details.

The bomb that was dropped over the Japanese city of Hiroshima in 1945 contained about 60 kilograms of uranium enriched to about 80 percent in fissile uranium-235. In that design, the uranium was initially in two pieces, and one was fired into the other to bring together enough material for a chain reaction to be set off. The resulting explosion released roughly the equivalent of 15,000 tons of chemical explosive.

The bomb that was dropped on Nagasaki, on the other hand, used plutonium rather than enriched uranium. It used the technique of implosion, where chemical explosives compress a sphere of plutonium. The compression reduces the spaces between the atomic nuclei and thereby the distance a neutron released in one fission has to travel before it causes another fission. Once the plutonium is sufficiently compressed, it becomes capable of sustaining a chain reaction. Practically any mixture of plutonium isotopes (plutonium-239, plutonium-240, plutonium-241, and even higher isotopes) can be used to make nuclear weapons.

The implosion technique is also used in modern nuclear weapons that use enriched uranium, because compression reduces the quantity of uranium required to set off a nuclear explosion. The uranium in modern nuclear weapons typically is enriched to a uranium-235 concentration of at least 90 percent.

The key metric that is used to measure the linkage between nuclear energy and nuclear weapons is called a “significant quantity”. The International Atomic Energy Agency defines a significant quantity as the approximate amount of fissile material “for which the possibility of manufacturing a nuclear explosive device cannot be excluded.” The significant quantities are 8 kilograms for plutonium and 25 kilograms of uranium-235 contained in highly enriched uranium, including losses during production. The definition is based on the Nagasaki design. More sophisticated nuclear weapon designs use smaller quantities of fissile materials.

A single 1,000-megawatt light-water reactor produces about 30 significant quantities of plutonium during each year of operation (see Figure 4.1). Although the purpose of the initial build-up of plutonium stockpiles globally was to manufacture weapons, since the end of the Cold War a second stockpile of plutonium from the reprocessing of civilian spent fuel has been growing rapidly. Roughly 30,000 significant quantities of plutonium were produced explicitly for nuclear weapon purposes. Reprocessing of spent fuel from civilian power reactors already has resulted in the separation of roughly 30,000 significant quantities of plutonium, approximately the same amount as what was produced for weapon purposes.

Until recently, those focused on the diversion of civilian nuclear materials to weapons use focused far more on plutonium than enriched uranium, because of the perceived difficulty of enriching uranium. In recent years, however, as centrifuge enrichment has become cheaper, the prospect of clandestine production of highly enriched uranium has resulted in the front and back ends of the fuel cycle receiving comparably intense attention.