Fundamentals of Nuclear Power

Juan S. Giraldo

Douglas J. Gotham

David G. Nderitu

Paul V. Preckel

Darla J. Mize

State Utility Forecasting Group

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Table of Contents

List of Figures

List of Tables

Acronyms and Abbreviations

ABWR	Advanced Boiling Water reactor
AGR	Advanced Gas cooled Reactor
AP	Advanced Passive 1000
APWR	Advanced Pressurized Water Reactor
BWR	Boiling Water Reactor
CANDU	CANada Deuterium Uranium
CNS	Convention on Nuclear Safety
CO_2	Carbon dioxide
COL	Combined Operating License
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
ESBWR	Economic Simplified Boiling Water Reactor
ESP	Early site permit
GFR	Gas-cooled fast reactor
GIF	Generation IV International Forum
HPM	Hyperion power Module
IAEA	International Atomic Energy Agency
INES	International Nuclear and Radiological Event Scale
INPO	Institute of Nuclear Power Operations
ISL	In situ leaching
kWh	Kilowatt-hour
LCOE	Levelized cost of electricity
LFR	Lead-cooled fast reactor
LTP	License termination plan
LWA	Limited work authorization
LWR	Light water reactor
MSR	Molten salt reactor
MW	Megawatts

MWh	Megawatt-hours
NO_x	Nitrogen oxides
NRC	U.S. Nuclear Regulatory Commission
O & M	Operating and maintenance
O_3	Ozone
PWR	Pressurized Water Reactor
PHWR	Pressurized Heavy Water Reactor
PM	Particulate matter
PRISM	Power Reactor Innovative Small Module
PSDAR	Post-shutdown decommissioning activities report
RBMK	Reaktor Bolshoy Moshchnosty Kanalny
RGGI	Regional Greenhouse Gas Initiative
SCWR	Super critical water cooled reactor
SFR	Sodium-cooled fast reactor
SO_2	Sulfur dioxide
TVA	Tennessee Valley Authority
US APWR	Mitsubishi Advanced Pressurized Water Reactor
US EPR	U.S. Evolutionary Power Reactor
VHTR	Very high temperature reactor
WANO	World Association of Nuclear Operators
WCI	Western Climate Initiative
WNA	World Nuclear Association

Glossary

Active safety systems: Safety systems that are activated by a human operator, an automatic – computer system or mechanically.

Capacity factor: The ratio of the actual output of a power plant over a period of time, over the potential output of the power plant had it operated at full nameplate capacity, expressed as a percentage.

Fissile material: Material capable of sustaining a chain reaction of nuclear fission.

Fuel rods: Long, slender, zirconium metal tubes containing pellets of fissionable material, which provide fuel for nuclear reactors.

Generation III$^+$: Reactors that have evolutionary improvements over currently operating reactors such as passive safety systems, increased thermal efficiency and standardized design.

NRC design certification: Approval of a nuclear power plant design, independent of an application to construct or operate a plant.

Nuclear material proliferation: The diversion or undeclared production of nuclear material, or misuse of technology, by states in order to acquire nuclear weapons or other nuclear explosive devices.

Operating factor: The ratio of the number of hours a unit was on-line to the total number of hours in a reference period, expressed as a percentage. It is a measure of the unit time availability on the grid and does not depend on the operating power level.

Passive safety systems: Safety systems that rely on the laws of nature such as gravity and natural circulation, to provide cooling for reactor in case of a power loss.

Uprate: The process of increasing the maximum power level at which a commercial nuclear power plant may operate.

Particulate matter: A complex mixture of extremely small particles and liquid droplets. It is made up of a number of components, including acids (such as nitrates and sulfates), organic chemicals, metals, and soil or dust particles.

Foreword

This report provides background on the current state of nuclear energy and consists of seven sections. Section one provides an overview of nuclear power generation in the U.S. and around the world. Section two offers an explanation of how nuclear power reactors are able to generate heat from the nuclear fission process, describes the two types of reactors, and describes the process of fabricating, using, and disposing of the nuclear fuel, which is a process known as the nuclear fuel cycle. Section three gives a description of the nuclear reactors that are currently operating both in the U.S. and around the world, a description of the new generation of reactors that are currently starting to be built, a description of a new concept for nuclear power generation, which is based on small modular reactors, and a brief description of the theoretical reactors that are expected to be built in the future. Section four discusses the costs of building a nuclear power plant and the economic competitiveness of nuclear power compared with other sources of generation. Section five gives a description of the licensing process for a nuclear plant and government incentives for the construction of nuclear plants. Section six describes the safety mechanisms that the nuclear industry uses to reduce the possibility of accidents and operate safely and lists some of the major commercial nuclear accidents. Section seven describes the final stage of a nuclear power plant, when it is decommissioned at the end of its generating life. A reference list, appearing the end of each section provides sources for more detail on the particular subject.

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For further information, contact SUFG at:

State Utility Forecasting Group
203 South Martin Jischke Drive
Mann Hall, Suite 154
West Lafayette, IN 47907-1971
Phone: 765-494-4223
Email: sufg@ecn.purdue.edu
https://www.purdue.edu/dp/energy/SUFG

Overview

1.1 Current state of nuclear power generation in the U.S.

Currently in the U.S. there are 65 nuclear power plants operating 104 nuclear reactors (see Figure 1-1). The last reactor to come into service was the Tennessee Valley Authority's (TVA) Watts Bar 1 in 1996. There is currently one nuclear reactor under construction that is projected to come into service by 2013 which is the Watts Bar 2 reactor in Tennessee [1]. The Watts Bar 2 reactor was a partially built reactor whose construction was stopped in 1988 due to a decrease in projected power demand [2].

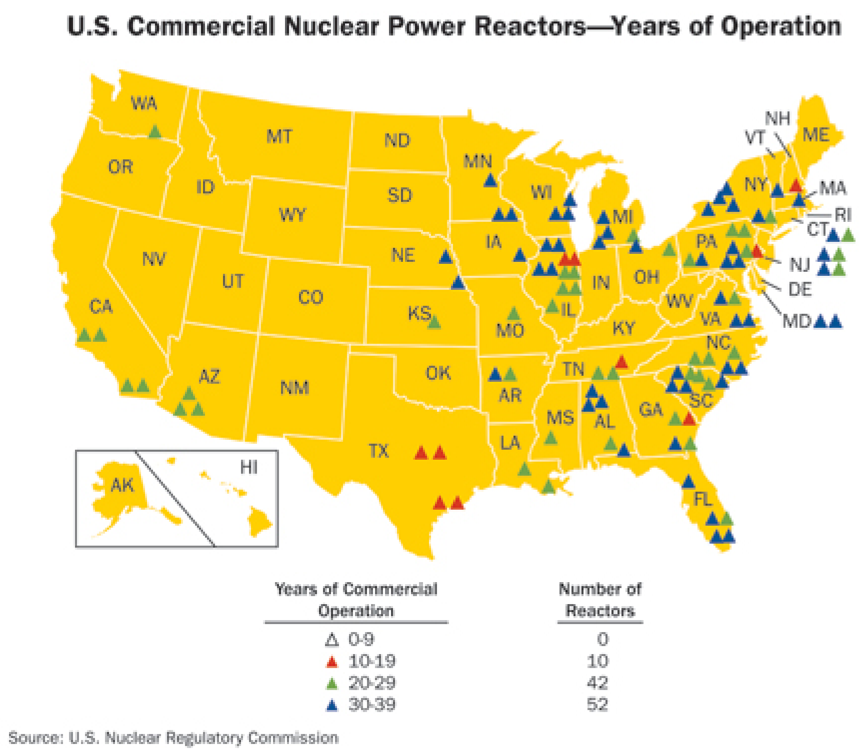

Figure 1-1: Location and years of operation for U.S. commercial power reactors
(Source: Nuclear Regulatory Commission [15])

In the U.S. there are only 2 kinds of nuclear reactors in commercial operation, the pressurized water reactor (PWR) and the boiling water reactor (BWR). Of the 104 operating reactors 69 are PWRs and 35 are BWRs [8].

Nuclear power plants represent 10 percent of the U.S. installed generating capacity yet they account for 20 percent of total U.S. electricity generation (see Figure 1-2). This is because nuclear power plants in the U.S are used much more intensively with very high capacity factors. The capacity factor of a generating unit is defined by the amount of electricity generated over a period of time divided by the amount the plant would have generated over that same period of time at its maximum rated capacity. Nuclear power plants have capacity factors of over 90 percent, a rate much higher than any other generation source [3]. Increased operating efficiencies and improved maintenance have resulted in increases in capacity factors from 56.3 percent in 1980, to 66 percent in 1990, to 91.1 percent in 2008 [3]. Another reason for the high capacity factors is that nuclear power plants have relative low fuel costs (per unit of energy generated) compared to other sources of generation, therefore it makes economic sense to operate them at high capacity factors [4]. Since 1990, output from nuclear plants has increased from 577 billion to 809 billion kilowatt hours (kWh), a 40 percent increase, despite very little new capacity having been installed [3].

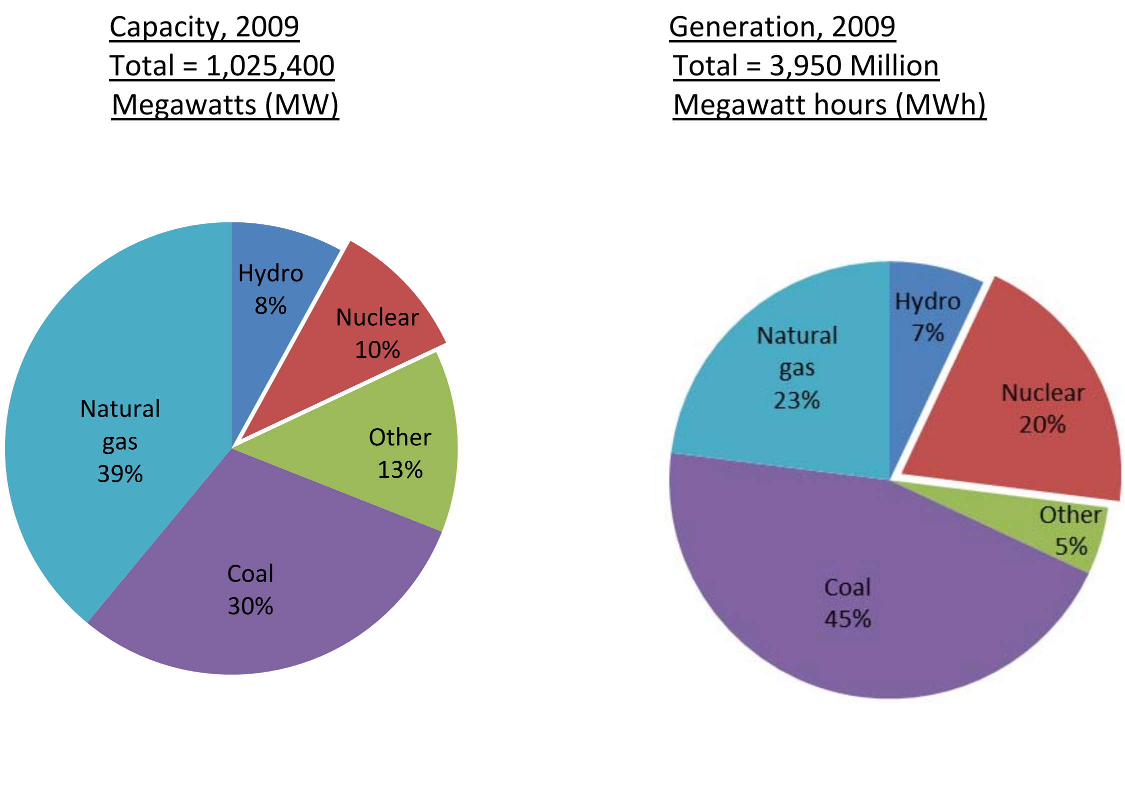

Figure 1-2: Capacity and generation of U.S. nuclear power plants (Data Source: EIA [1])

Output from nuclear power plants is expected to increase further due to the implementation of power uprates. When the Nuclear Regulatory Commission (NRC)[1] issues an operating license, it sets a limit on the maximum heat output, or power level, for the reactor core. This limit is set because many of the safety analyses are demonstrated for a specific power level. If an operator wants to increase the amount of heat output of the reactor core, a power uprate, it can do so only after approval of the NRC [5]. As of April 2011 the NRC had approved 139 uprates that collectively represent approximately 6,020 MW, roughly equivalent to the capacity of 6 nuclear power reactors [5].

Most of the operating nuclear power reactors were constructed during the late 1970s and 1980s, and their 40 year operating licenses were due to expire before 2020. The NRC has been granting 20 year operating license extensions to increase the operational life of nuclear reactors to 60 years. So far 71 reactor license extensions have been granted, 13 reactors have filed for extensions, and 19 more reactors are expected to file for extensions. The NRC has approved all of the applications for license extensions for which the review has been completed [17]. Only two reactors are expected to end their service before 2020; the Kewaunee Power Station in Wisconsin is scheduled to be shut down in 2013 and the Oyster Creek Generation station in New Jersey is expected to operate until the end 2019 [6, 22]. The Kewaunee plant, which consists of a single 556 MW unit, is being decommissioned due a combination of low wholesale electricity prices in the region and a lack of economies of scale [22]. The San Onofre Nuclear Generating Station in California was shut down in January 2012 due to equipment problems. The NRC has placed the plant in an enhanced regulatory status and the future status of the station is unknown [23].

Since 2007 and as of October 2011 there have been 17 applications to the NRC for new nuclear power plants (see Table 1-1) [21]. Several have been suspended by the utilities that submitted the applications and two have had completed reviews and have construction well under way (Vogtle in Georgia and Summer in South Carolina) [3, 7]. A Combined Operating License (COL) and Limited Work Authorization (LWA) were issued for the Vogtle site on February 10, 2012. A COL was issued for the Summer site on March 30, 2012.

[1] The NRC is the government agency that formulates policies, regulates, issues licenses and adjudicates legal matters in the nuclear power industry.

Company	Site	Design	Units	Application status
Southern Nuclear Operating Company	Vogtle,GA	AP1000	2	Review Complete
South Carolina Electric and Gas	Summer, SC	AP1000	2	Review Complete
Duke Energy	Levy County, FL	AP1000	2	Under Review
Duke Energy	Lee, SC	AP1000	2	Under Review
Duke Energy	Harris, NH	AP1000	2	Under Review
Florida Power & Light	Turkey Point, FL	AP1000	2	Under Review
TVA	Bellafonte, AL	AP1000	2	Suspended
Dominion	North Anna, VA	US APWR	1	Under Review
Luminant	Comanche Peak, TX	US APWR	2	Under Review
STP Nuclear Operating Company	South Texas Project, TX	ABWR	2	Under Review
TVA, TN	Clinch river	mPower	6	Expected in 2016
Union Electric Company	Callaway, MO	US EPR	1	Suspended
Unistar Nuclear Operating Services	Calvert Cliffs, MD	US PR	1	Under Review
Entergy Operations	Grand Gulf, MS	ESBWR	1	Suspended
Detroit Edison Company	Fermi, MI	ESBWR	1	Under Review
Entergy Operations	River Bend, LA	ESBWR	1	Suspended
Unistar Nuclear Operating Services	Nine Mile Point, NY	US EPR	1	Under Review
PPL Bell Bend	Bell Bend, PA	US EPR	1	Under Review

Table 1-1: Nuclear Power Plant Applications (Data source: NRC [21])

1.2 Nuclear power around the world

There are 440 nuclear reactors in commercial operation in 31 countries, providing 14 percent of the world's electricity (see Figure 1-3) [9]. The U.S. generates the largest amount of electricity from nuclear power in the world, about one-third of the world's generation, followed by France with approximately half of the U.S. output. However, some other countries are far more dependent on nuclear power such as France which relies on nuclear power for about 80 percent of its electricity needs (see Figure 1-4) [9]. There are currently 60 reactors under construction in 15 countries. Construction is particularly significant in China with 27 reactors under construction and several more expected in 2012. Russia has 10 reactors under construction, South Korea has 5 and India has 6 [10].

Before the 2011 Fukushima nuclear accident, Japan's plans were to increase nuclear power's share of electricity from 30 percent to over 40 percent before 2020 [17]. Following the accident the Japanese government announced plans for a new energy policy that aimed to reduce Japan's dependency on nuclear energy as much as possible. On September 2012, an advisory Cabinet panel endorsed a policy that would see nuclear energy completely phased out sometime in the 2030s. However, the Japanese Cabinet has not fully committed to the panel's recommendation. The future of Japan's nuclear energy is still subject to ongoing political debate [20]. Following the Fukushima accident all of Japan's 50 reactors were shut down for safety checks and only two were restarted in July 2012 in order to prevent possible power outages [18, 19].

It is expected that the 2011 Fukushima accident will slow construction of new nuclear reactors, especially in Europe and Japan, but in other places it is expected to only temporarily delay construction due to safety reappraisals [11]. Nonetheless two countries have decided to end their nuclear energy programs after the Fukushima accident. Germany plans to shut down all of its 17 nuclear reactors by 2022, and the Swiss cabinet ruled that replacements for their aging reactors would not be built, effectively ending the country's nuclear program by 2034 [12]. Belgium's Government is also considering ending their nuclear power program but has not agreed to a date to end operations. This is not related to the Fukushima accident as Belgium's government has been planning the closures since 2003 [13].

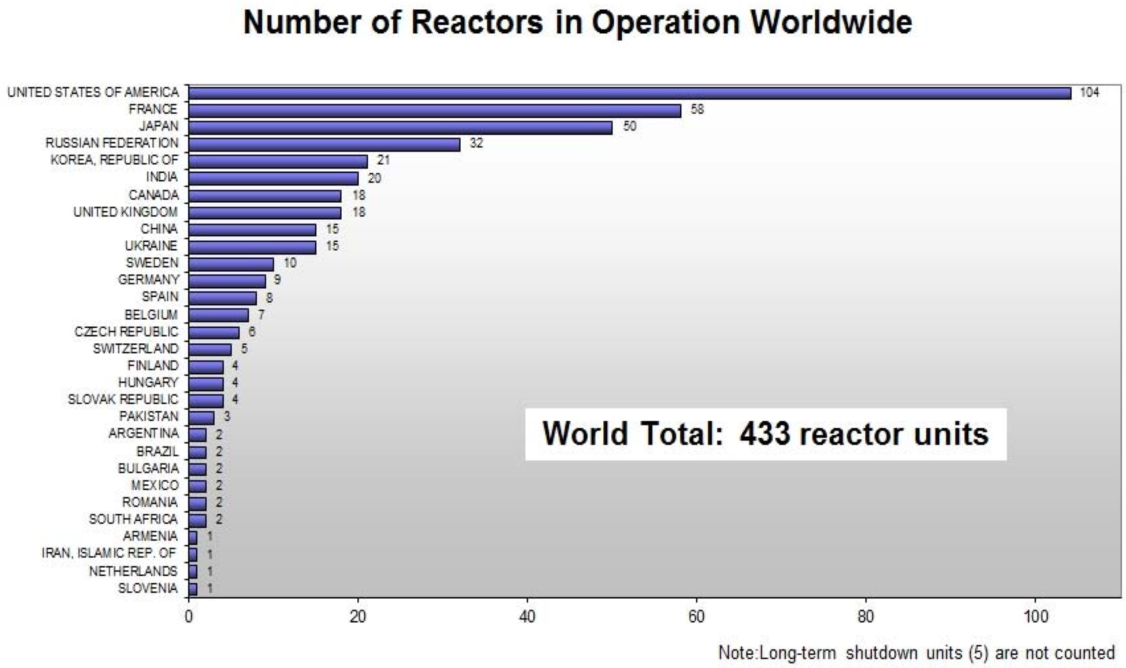

Figure 1-3: Number of reactors in operation worldwide (Source: IAEA [14])

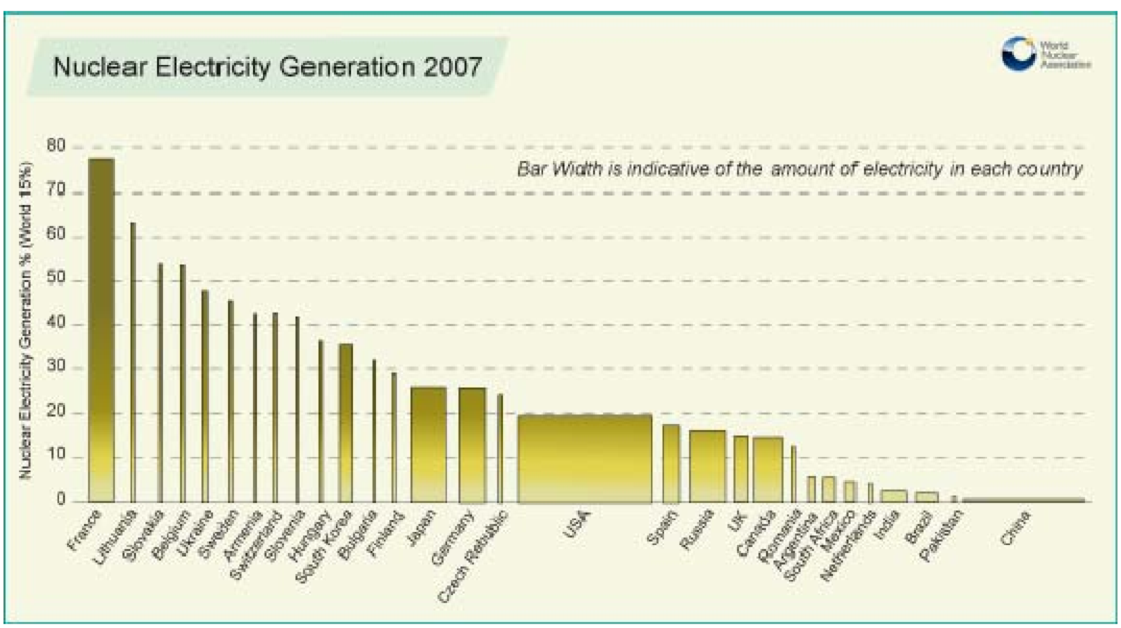

Figure 1-4: Share of nuclear power generation in countries with nuclear power (Source: World Nuclear Association [9])

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2. Nuclear Energy

2.1 How nuclear power plants generate electricity

Nuclear power plants generate electricity in much the same way that other thermal power plants generate electricity. The combustion of a fuel is used to generate heat, the heat is used to create steam, and the steam is used to spin turbines, which in turn generate electricity. The difference with nuclear power plants is that instead of using the combustion of a fuel to generate heat, they use nuclear fission to generate heat. Nuclear fission in simple terms is the splitting of large atoms into smaller atoms; this process releases vast amounts of energy.

2.2 Radioactive decay

Nuclear fission can occur either naturally or be induced. When it happens naturally the process is known as radioactive decay, and it is a common process. The elements in which this process occurs naturally are known as radioactive isotopes. These radioactive isotopes are atoms that have an unstable nucleus because the nucleus has an excess amount of energy. This instability will cause them to spontaneously decay or "split" into two smaller atoms. These newly formed atoms will be of different elements from the original radioactive isotope and their nuclei will be more stable. It is not possible to predict when a specific radioactive isotope will decay, however the average rate at which it will decay is known; this rate is referred to as the "half-life". Half-life refers to the amount of time for a specific quantity of a decaying substance to be reduced by half. Half-lives can vary greatly and range from mere seconds to millions of years. One example of naturally occurring radioactive decay is that of carbon-14. Cabon-14 occurs naturally in the atmosphere, and it is present in living things at a very specific proportion. Carbon-14 is used to estimate the age of organic remains by measuring the amount of carbon-14 remaining in a fossil and comparing it to the amount that it would have had at the time of death. Since the half-life of carbon-14 is known, by knowing how much carbon-14 has decayed, an estimate of how much time it would have taken for that to happen can be made.

2.3 Nuclear reaction

The other type of nuclear decay called fission is a manmade nuclear reaction. This reaction occurs inside the nuclear reactor and generates the heat to produce electricity. A nuclear reactor is the steel vessel where the nuclear fuel is contained. A nuclear reaction occurs when an atom is induced to split or "fission", and as a consequence, it releases a large amount of energy. Substances that are able to be induced to split are known as fissile materials, and it is out of fissile materials that nuclear fuel is made. The nuclear fuel most commonly used for commercial nuclear power plants is uranium (denoted by the chemical symbol U). Uranium is a metallic chemical element commonly found on the earth's crust. Naturally occurring uranium comes in three different varieties or isotopes. All uranium isotopes contain 92 protons in their nucleus (which is what makes them uranium); the difference between the isotopes is the number of neutrons in the nucleus. Naturally occurring uranium include U-234, with 142 neutrons, U-235 with 143 neutrons and U-238 with 146 neutrons. In nature 99.3 percent of the uranium is U-238, 0.7 percent is U-235 and less that .01 percent is U-234 [18]. U-235 is the only fissile, naturally occurring uranium isotope, and it is therefore the most commonly used nuclear fuel.

A nuclear reaction starts with a U-235 atom that is induced to split by shooting a neutron at it. When the U-235 atom absorbs the neutron it momentarily becomes a U-236 atom. The nucleus of the U-236 atom is relatively unstable, and it quickly breaks up into two different atoms and releases two to three free neutrons in the process (see Figure 2-1). The newly formed atoms are known as fission products and they will be roughly half the size of the original atom. Fission products will vary with each fission reaction and will range from elements with atomic number 30 (Zinc), to atomic number 71 (lutetium).

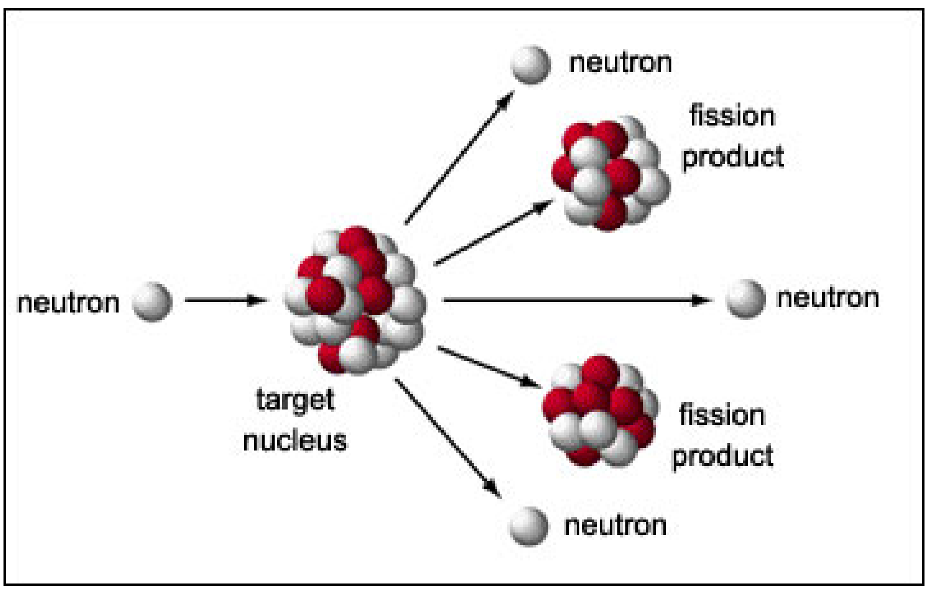


Figure 2-1: Nuclear fission (Source: atomicarchive.com [22])

The free neutrons that are released are very important for the continuation of the nuclear reaction or what is known as a nuclear chain reaction. A chain reaction occurs when the neutrons released by the fission of a U-235 atom are absorbed by other U-235 atoms, causing further fission reactions, which in turn release more neutrons and cause further fission reactions (see Figure 2-2).

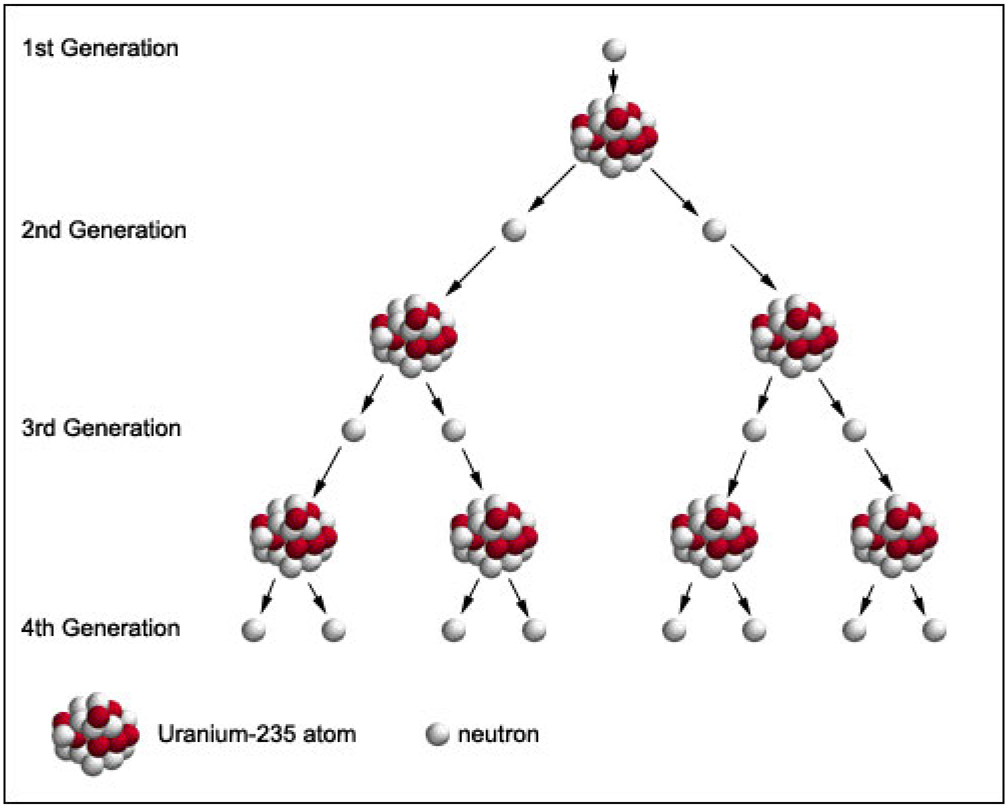


Figure 2-2: Nuclear chain reaction (Source: atomicarchive.com [22])

Even though two to three neutrons are released by every fission reaction, not all of them will cause another reaction. If it happens to be the case that the rate at which the neutrons are being lost is greater than the rate at which they are being released, the reaction will not be self-sustaining. When these two rates are equal and the reaction becomes self-sustaining, the reaction is said to have reached criticality [20].

A situation where the rate at which neutrons are being released is greater than the rate at which they are being lost can also occur. This could lead to an uncontrolled reaction. In order for the reaction to become self-sustained at a leveled point, only one neutron of the two to three released must be allowed to hit another U-235 atom. To accomplish this, control rods, made of neutron absorbing materials, are used to control the rate of the reaction, or to halt it, by inserting or removing them from the reactor core [1]. When the control rods are inserted, they absorb more neutrons, so fewer neutrons are available for absorption into the fuel; thus, there are fewer reactions and the power generated is reduced. Similarly, withdrawing the control rods increases the power output. There are two types of nuclear reactors, thermal or slow neutron reactors and fast reactors.

2.4 Thermal reactors

Thermal reactors use slow neutrons to sustain the nuclear chain reaction. The speed at which the neutrons are released by the fission reaction is too fast to be absorbed by other U-235 atoms. In order to slow down the neutrons the fuel is contained within a "moderator" so that a continuous chain reaction can be maintained. The moderator is usually water, but heavy water (water whose hydrogen atoms contain both a proton and a neutron as opposed to just one proton) and graphite are also used. In addition to serving as the moderator, water in thermal reactors also serves as the coolant. Water inside the reactor is constantly flowing to both cool the reactor and capture the thermal energy to produce electricity. Both thermal and fast reactors must constantly be cooled, even when shutdown, because of the heat generated by the radioactive decay of the fission products. Thermal reactors are the ones that are currently being used for commercial operations since the technology to make fast reactors economically viable is not yet available.

2.5 Fast reactors

As opposed to thermal reactors, fast reactors can sustain a nuclear chain reaction using the fast neutrons, thus they have no need for a moderator. However in order to maintain the nuclear chain reaction using fast neutrons a fuel that is richer in fissile materials is needed. Fast reactors can use either a fuel that has a higher concentration of U- 235 (20 percent or higher as opposed to 3-5 percent for thermal reactors) or plutonium-239 (Pu-239). Pu-239 is more suitable for fast reactors because it releases 25 percent more neutrons per fission than U-235. Even though there is less neutron absorption because of the higher speed of the neutrons, this is compensated by the higher amount of neutrons released and the nuclear reaction is able to be maintained. Since fast reactors depend on fast neutrons, in order to avoid any type of moderation, a liquid metal (usually sodium) is used as the coolant instead of water. A liquid metal is also a more efficient medium for transferring heat [19].

Pu-239 is one of the three isotopes that can be used as nuclear fuel (U-233 is the other one). Pu-239 is not a naturally occurring isotope but rather it is created in either special plutonium producing reactors or as a byproduct of thermal reactors. Plutonium producing reactors use the fission of U-235 to convert U-238 into Pu-239. This occurs when one of the neutrons given off by the fission of U-235 is absorbed by an atom of U-238 and it becomes a Pu-239 atom. In commercial thermal reactors this same process occurs with the U-238 in the nuclear fuel but at a much lower level. Fast reactors are also used to produce or "breed" Pu-239 by placing a "fertile blanket" of depleted U-238 around the core. The U-238 absorbs some of the free neutrons given off by the Pu-239, and it eventually turns into Pu-239. This blanket is then removed from the reactor and processed to make more fuel for either the reactor itself, or for other fast reactors. Fast reactors that are able to produce (breed) more Pu-239 than they consume are known as Fast Breeder Reactors (FBRs) [19].

Because fast reactors use Pu-239 as their main fuel they are being considered as a means of dealing with the nuclear waste generated by thermal reactors. When spent nuclear fuel is removed from thermal reactors about one percent is Pu-239. Since Pu-239 is highly radioactive and has a half-life of 24,000 years [21], storing it safely is very expensive. The idea is to remove the Pu-239 from the spent fuel and use it as fuel for fast reactors. This is seen as beneficial not only because it gets rid of the most hazardous waste, but it also lowers the cost of storing the remaining fuel and reduces the possibility of nuclear materials proliferation [19].

2.6 Nuclear fuel cycle

Nuclear power plants use uranium as fuel to generate electricity. Uranium is a mildly radioactive metal that is very common on the earth's crust. Before it can be used as nuclear fuel uranium must be extensively processed. The various stages that uranium goes through in the process of generating electricity are known as the nuclear fuel cycle. At the front end of the cycle are the activities related to the production of nuclear fuel; the service period is when the nuclear fuel is being used to generate electricity; and the back end of the cycle refers to the storage, reprocessing and final disposition of the spent nuclear fuel.

2.7 Front end

- Mining: Uranium mining is done with either traditional mining techniques, such as underground or open pit, or more commonly using a mining technique known as in situ leaching (ISL). ISL involves circulating oxygenated ground water through the porous ore deposit; dissolving the uranium oxide and bringing it to the surface (see Figure 2-3). The solution is then extracted and taken to a mill for further processing [1]. In 2010, U.S. operators of civilian nuclear reactors purchased the equivalent of 47 million pounds of uranium, most of which was imported. Eight percent came from the U.S.; 41 percent came from Kazakhstan, Russia and Uzbekistan; 37 percent came from Australia and Canada; and 14 percent came from Namibia, Niger and other countries [2]. While the U.S. has sufficient uranium resources to increase domestic production, deposits in other countries are larger and cheaper to mine.

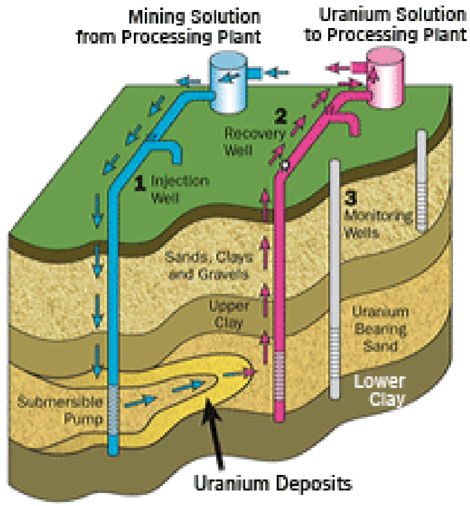


Figure 2-3: Mining via in situ leaching (Source: Nuclear Regulatory Commission [12])

- Milling: The ore or solution is then taken to a mill to be processed into uranium oxide concentrate, known as 'yellow cake' (U_3O_8) (see Figure 2-4), which contains more than 80 percent uranium. Yellow cake is packed into 200- liter drums and shipped to a conversion facility. The milling process creates a waste byproduct known as uranium tailings, which is the residual ore material. These tailings contain radium, which decays into the radioactive gas radon, and other toxic materials such as heavy metals [3]. Tailings pose a potential safety and public health hazard, and for that reason they are isolated in engineered facilities near the mine (usually the open pit) [1].

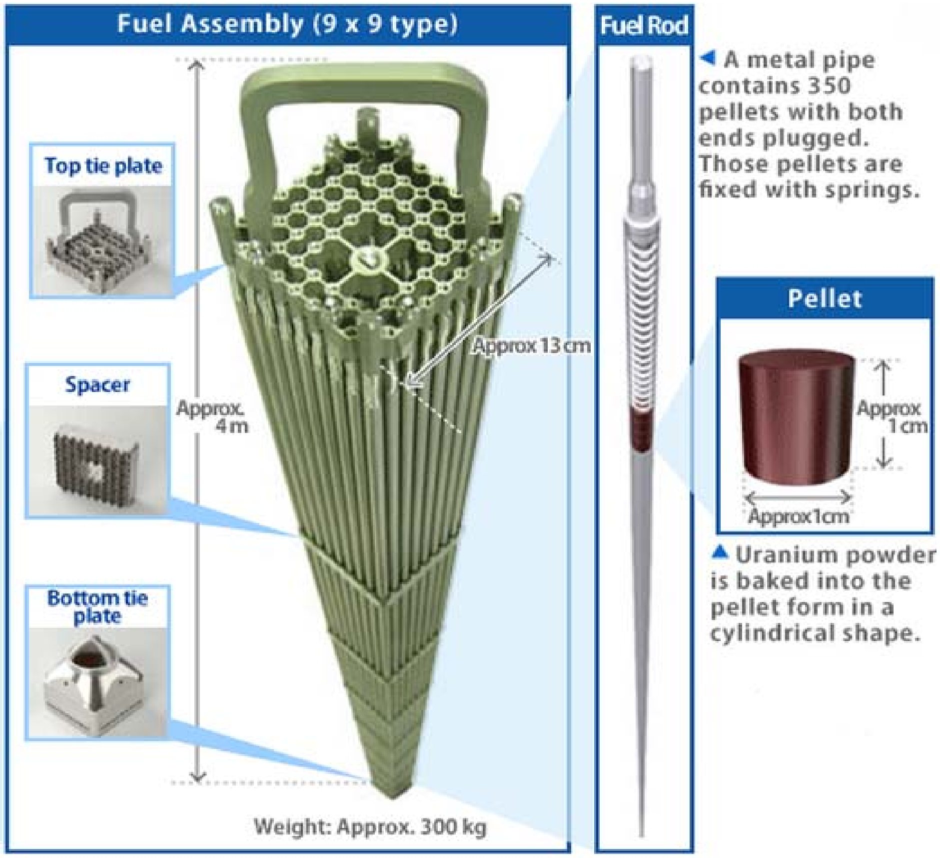
Figure 2-4: Uranium oxide concentrate (U_3O_8) (Source: World nuclear news [13])

- Conversion: At the conversion facility yellow cake uranium is turned into uranium hexafluoride (UF_6) gas. This is necessary in order to enrich the uranium. During the conversion process impurities are removed and the uranium is combined with fluorine to produce the UF_6 gas. The gas is then pressurized, cooled to a liquid, and drained into 14-ton cylinders where it solidifies. The cylinder is then shipped to an enrichment facility. Currently in the U.S. the only conversion facility is in Metropolis, Illinois [4].

- Enrichment: The UF_6 gas coming from the conversion facilities is known as natural UF_6 because it still contains the natural concentration of uranium isotopes, which is about 99.27 percent uranium-238 (U-238), 0.72 percent uranium-235 (U-235) and less than .01 percent uranium-234 (U-234). The fuel for most nuclear reactors must have a higher concentration of the fissionable U-235 in order to start and sustain a nuclear reaction.[2] The UF_6 gas can be enriched by three different processes: gaseous diffusion, gas centrifuge, or laser separation. The final product is an 'enriched' UF_6 gas with a U-235 concentration of 4 to 5 percent, which is stored in a canister, allowed to cool and solidify, and shipped to a fuel fabrication facility. The only operating fuel enrichment facility in the U.S. is in Paducah, Kentucky; however, two gas centrifuge enrichment facilities are currently under construction [5].

Fuel fabrication: The fuel fabrication facilities receive the UF_6 gas in solid form; they then heat it to a gaseous form, and chemically process it to turn it into uranium dioxide (UO_2) powder. The powder is then compressed into pellets and sintered to a ceramic form. Sintering is the process of bonding metal particles by using heat and pressure. The pellets are then stacked and sealed into long zirconium alloy tubes about 1 centimeter in diameter to form a fuel rod. Fuel rods are then bundled into fuel assemblies, which depending on the reactor design, can have between 179 and 264 fuel rods per fuel assembly (see Figure 2-5). A typical reactor core can hold 121 to 193 fuel assemblies. The U.S currently has five fuel fabrication facilities [6, 7].

[2] Heavy water reactors are capable of sustaining reactions at naturally occurring concentrations of U-235. See section 3 for a discussion of reactors types, including heavy water reactors.



<u>**Figure 2-5**: Fuel assembly</u> (Source: Nuclear Fuel Industries, Ltd [14])

2.8 Service period

The fuel assemblies are shipped by truck to the reactor sites where they are stored in "fresh fuel" storage bins until needed by the reactor operator. At this stage the fuel assemblies are only mildly radioactive; all the radiation is contained within the tubes. When needed for service the fuel assemblies are inserted into the reactor core which is itself a cylindrical arrangement of fuel bundles. Just by placing the fuel bundles next to other fuel bundles and adding water a nuclear reaction is initiated. Typically about one third of the fuel assemblies (40 to 90) in a reactor core are replaced every 12 to 24 months [7].

2.9 Back end

- <u>Interim storage:</u> Fuel assemblies will spend 18 to 36 months inside the reactor core, after which they are removed from the reactor and stored in special pools in the reactor building (see Figure 2-6). Inside the reactor the fuel assemblies become highly radioactive, and even though the fission process has stopped they continue to emit heat from the radioactive elements. It is necessary to store them in pools both to cool the fuel and protect the workers from any radiation. The fuel assemblies must be stored at a depth of at least 20 feet to provide sufficient radiation protection. The fuel assemblies will typically be stored in the spent fuel pools for about five years to allow them to cool. When they have cooled enough, the fuel assemblies are moved to a dry cask for further on-site storage (see Figure 2-7). Each cask is designed to hold from 24 to 72 spent fuel assemblies. When the fuel assemblies are placed in the casks the air and water are removed, they are filled with inert gas, and sealed shut by either welding or bolting [1, 7, 8, and 9].

Figure 2-6: Spent fuel storage pool (Source: International Atomic Energy Agency [15])

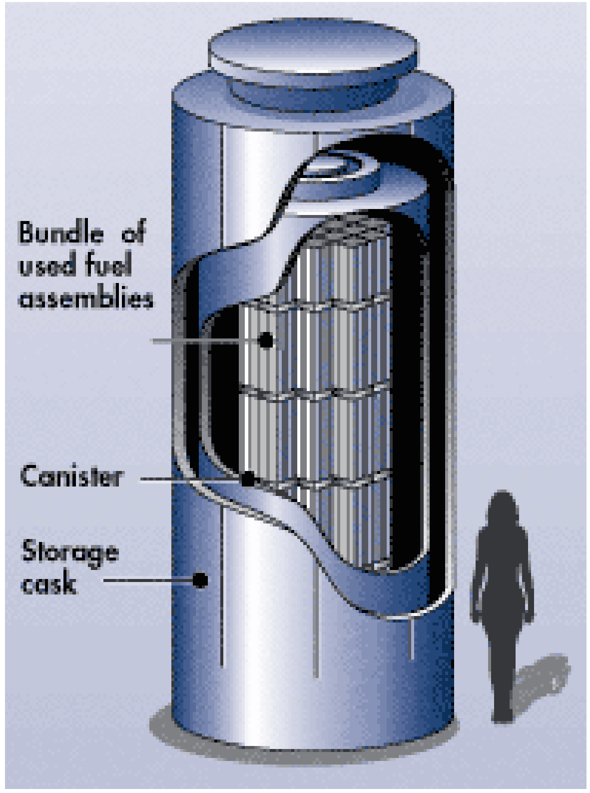


Figure 2-7: Dry cask storage (Source: NRC [16])

- Reprocessing: Not all of the U-235 uranium in the fuel rods is consumed in the nuclear reactor. The spent fuel rods contain approximately 1 percent U-235 and 1 percent plutonium. These can be reprocessed in order to extract the fissionable materials to be used in the production of fresh fuel assemblies. Nuclear fuel reprocessing is done in some countries such as France. In the past there has been some nuclear fuel reprocessing in the U.S.; however it was banned in 1977 in compliance with nuclear non-proliferation policy. There were concerns that the plutonium extracted from the spent fuel could fall into the wrong hands and be used to manufacture nuclear bombs [10].

  Reprocessing activities determine if there is an 'open' or 'closed' fuel cycle. In an open or 'once-through' fuel cycle the spent nuclear fuel is not reprocessed. If the fuel is reprocessed and any part of it is reused in a reactor, the cycle is referred to as a closed fuel cycle [15].

- Final disposal: The final step of the fuel cycle would be the disposal of the spent fuel assemblies and any remaining high-level nuclear waste in a permanent underground repository. The U.S. does not currently have such a repository, and there is much controversy around the issue. The Nuclear Waste Policy Act of 1982 established that the federal government was to take responsibility of all used civilian nuclear fuel and store it at two permanent repositories beginning in 1998. The repositories were to be paid for by a 0.1 cent/kWh fee charged to the utilities that would go into the Nuclear Waste Fund. The Yucca Mountain site in Nevada was chosen in 1997, and a construction license was submitted to the NRC in 2008. Some construction was done at the site, but in 2009 the project was defunded by the Obama administration on grounds that there might be better alternatives to the long-term disposal of nuclear fuel. By the beginning of 2010, utilities had contributed over $31 billion (including interest) to the Nuclear Waste Fund, of which $24 billion remain after the money that was spent on the Yucca Mountain project. Storage alternatives are being considered, but there is still no long-term solution [10]. Nuclear power plant operators are resorting to building Independent Spent Fuel Storage Installations (ISFSI) at their sites and keeping the spent fuel there until a permanent repository is developed (see Figure 2-8). Through the "waste confidence decision," which is a generic action through which the NRC expresses that it found reasonable assurance that the waste can be stored safely and with minimal environmental impacts, the NRC has determined that the fuel can be stored safely for 60 years beyond the reactor's licensed life in these facilities, which are licensed separately from the nuclear power plant. Taking into account 40 years of initial reactor operation and 20 years of extended operation, the fuel can be stored for up to 120 years. However, the NRC licenses or certifies the dry cask for 20 years with possible renewals for up to 40 years. This means that dry casks are inspected to ensure adequate management as they age [11].

Figure 2-8: Dry storage at the Connecticut Yankee site (Source: Connecticut Yankee [17])

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3. Nuclear Reactors

3.1 Technologies currently being used in the U.S.

Currently in the U.S. there are only 2 types of commercial reactors in operation, the pressurized water reactor (PWR) and the boiling water reactor (BWR). These two types of reactors fall into the broader category of light water reactors (LWRs). LWRs use conventional water as both a moderator and a coolant [1].

- The pressurized water reactor: The pressurized water reactor has two separate coolant loops that never mix (see Figure 3-1). The primary coolant loop contains pressurized water that runs through the reactor core and carries the heat to the steam generator. Inside the steam generator heat is exchanged between the two separate loops; steam is created and carried through the second coolant loop to the main turbine generator, generating electricity. The exhaust is taken to a condenser where it condenses back to water and is pumped back into the steam generator. The primary coolant returns to the reactor to complete the cycle [2].

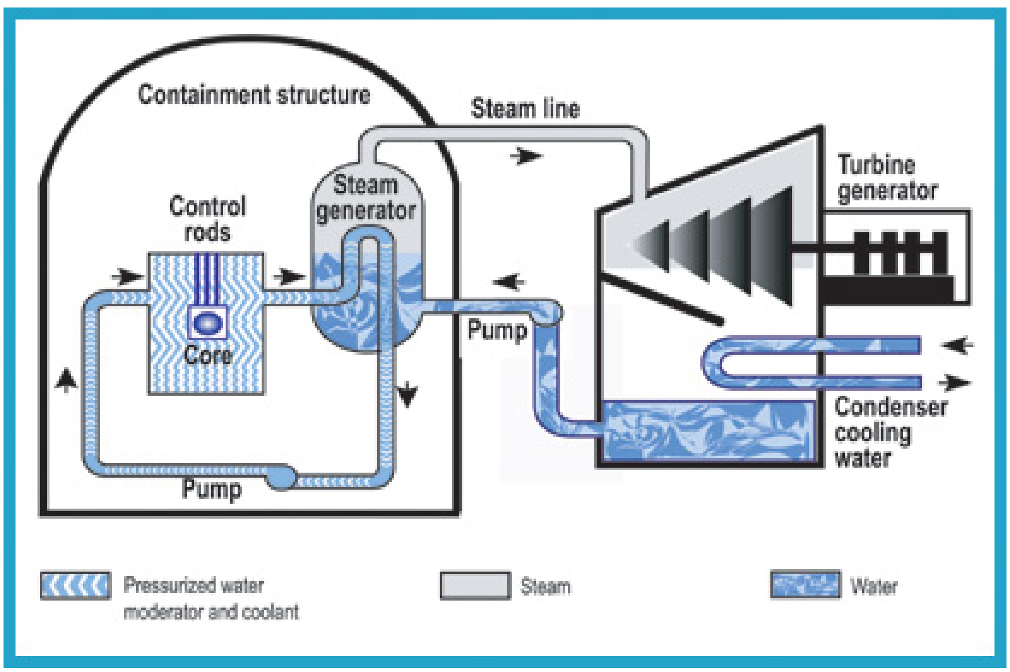

Figure 3-1: Pressurized water reactor (Source: World Nuclear Association [20])

- The boiling water reactor: The boiling water reactor uses only a single coolant loop (see Figure 3-2). Inside the reactor core heat is generated, coolant is pumped into the bottom of the reactor, and it absorbs heat as it moves upward through the reactor core. A steam-water mixture is created, and it leaves the top of the core where it enters a two stage moisture separation process where water droplets are removed, and steam is allowed to enter the steam line. The steam line then directs the steam to the turbines where electricity is generated. The exhaust steam is directed to a condenser where it is condensed back into water, and it is pumped through the system again. BWRs are typically larger than PWRs and can hold between 370 to 800 fuel assemblies, compared to 150 to 200 in PWRs [3].

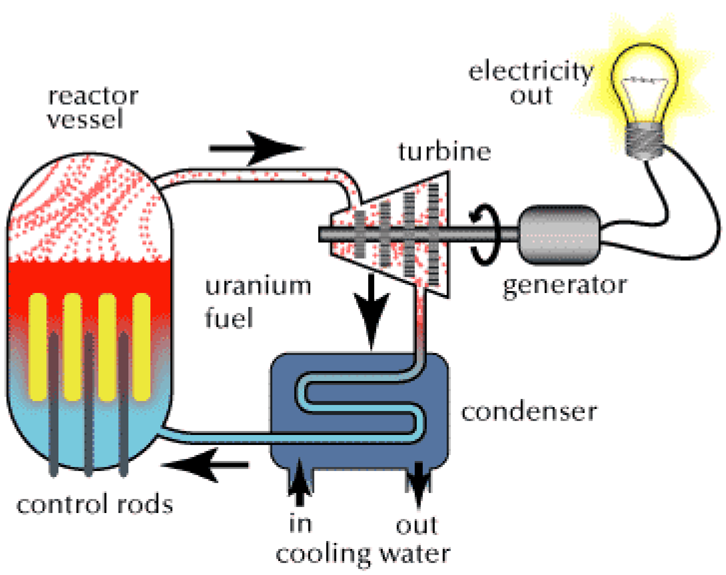

Figure 3-2: Boling water reactor (Source: University of Wyoming GeoWeb [21])

3.2 Technologies currently being used around the world

In addition to PWRs and BWRs there are other nuclear power technologies in commercial operation elsewhere including: the CANDU reactor, the advanced gas cooled reactor, and the RBMK (Reaktor Bolshoy Moshchnosty Kanalny) reactor.

- The pressurized heavy water reactor (PHWR) or "CANDU" reactor (short for Canada deuterium uranium): This technology was developed in Canada, and there are 44 units in operation [4]. The CANDU Reactor operates much like a PWR, but instead of using conventional "light" water as a moderator, it uses heavy water (known as deuterium oxide) as a moderator. Deuterium is a form of hydrogen where the nucleus contains both a proton and a neutron as opposed to the more common form which only has a single proton. The moderator is used to slow down neutrons so that a sustained nuclear chain reaction can occur; with conventional “light” water many of the neutrons are lost as they are absorbed by the hydrogen atoms in the water molecules. Since heavy water already contains an extra neutron in the hydrogen nuclei, lower neutron absorption occurs, allowing more free neutrons to create fission reactions. With fewer neutrons being lost to absorption, CANDU reactors can use natural uranium as fuel (which contains 0.07 percent U-235), instead of enriched uranium (which contains 2 percent to 4 percent U-235) that is used by PWRs and BWRs. This translates into cost savings because the uranium enrichment process can be very expensive [5]. CANDU reactors can also use other low-fissile content fuel, such as spent fuel from light water reactors [6].

- <u>The advanced gas cooled reactor (AGR):</u> Developed in the United Kingdom, there are currently 14 AGR units operating there, and all are expected to end operations by the end of 2023 [7]. AGRs use graphite as a moderator and carbon dioxide as the coolant. The carbon dioxide circulates through the reactor core and then past steam generator tubes outside of the reactor but inside the concrete pressure vessel (see Figure 3-3). The steam is then directed to a turbine generator [8].

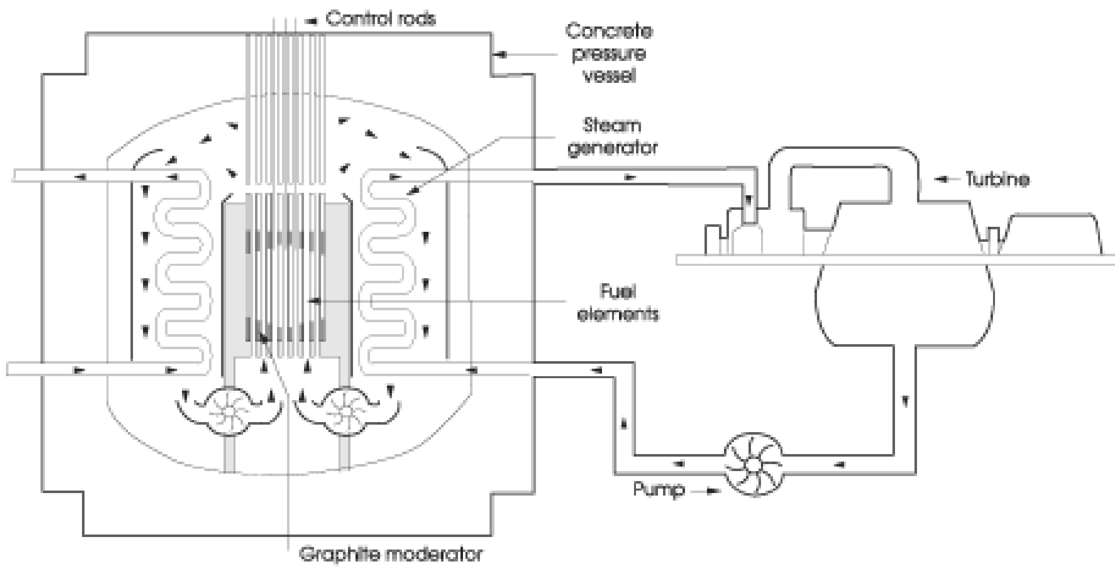

Figure 3-3: <u>Advanced gas cooled reactor</u> (Source: World Nuclear Association [8])

- <u>The light water graphite-moderated reactor or reactor Bolshoy Moshchnosty Kanalny (RBMK):</u> Developed in the Soviet Union, this design is a type of pressurized water reactor that uses water as the coolant and graphite as the moderator. Each fuel assembly is located in its own pressure tube or channel, and each channel is individually cooled by water. It was an RBMK reactor that was involved in the Chernobyl accident; however major modifications were made to the reactors to address the safety issues.[3] Currently there are 11 RBMK reactors in operation in Russia [9].

3.3 New nuclear technology

Nuclear reactors that are currently being built and nuclear reactors that are expected to be deployed in the short to medium-term are part of a new generation of nuclear reactors known as Generation III$^+$ reactors. These reactors are based on improved designs from currently operating reactors and are characterized by:

- Standardized designs intended to expedite the licensing process, reduce capital and constructions costs, and reduce construction time;
- Simpler designs that make them easier to operate and less vulnerable to operational interruptions;
- Digital instrumentation and controls that allow for more accurate and reliable plant monitoring, control and diagnostics;
- Passive safety systems, which rely on gravity, natural circulation and compressed gases to keep the core and containment structure from overheating in case of shutdown (these differ from active safety systems which rely on pumps and diesel generators in the event power is lost); and
- Expected operational life of 60 years.

Some of the most prominent Generation III$^+$ designs are the Advanced Boiling Water Reactor, the Advanced Passive 1000 reactor, the Economic Simplified Boiling Water Reactor, the U.S. Evolutionary Power Reactor, and the Mitsubishi Advanced Pressurized Water Reactor. A number of the Generation III$^+$ designs incorporate the concept of modularity, which allows for smaller sized reactors that can be manufactured off-site.

- The advanced boiling water reactor (ABWR): The ABWR is offered by GE Hitachi Nuclear Energy and Toshiba. The ABWR is a Generation III$^+$ evolutionary reactor based on the BWR. It offers improved electronics; computer, turbine, and fuel technology (see Figure 3-4). Enhancements include the use of internal recirculation pumps, microprocessor-based digital control and logic systems, and digital safety systems. Safety enhancements include protection against over pressurizing the containment vessel, passive core flooding

[3] For instance, the Chernobyl reactor did not have a containment structure like other reactor designs have. See section 6 for a more complete discussion of reactor safety and accidents.

capability, three emergency diesel generators, and a combustion turbine as an alternative emergency power source [10]. Vendor figures for the power output are between 1,350 and 1,460 MW with a capacity factor greater than 90 percent [11].

There are currently 4 ABWR reactors in operation in Japan and several others under construction in Japan[4] and Taiwan. They are the first Generation III$^+$ reactors to be built with the first one completed in 1996. There have been reliability issues with the operating ABWRs related to technical problems that have caused repeated shutdowns. As a result, operating and capacity factors have been rather low (see Table 3-1).

The ABWR was issued a design certification by the NRC, meaning that the NRC has approved the reactor design. This is done to help expedite the construction of new nuclear power plants.

Reactor	Commercial operation date	Operating factor (%)	Capacity factor (%)
KASHIWAZAKI KARIWA-6	Nov, 1996	72.1	72.8
KASHIWAZAKI KARIWA-7	Jul, 1997	68.5	68.2
SHIKA-2	Mar, 2006	44.9	44.0
HAMAOKA-5	Jan, 2005	43.6	44.6

Table 3-1: Japan's ABWRs' operating and capacity factors [12].

[4] Construction in Japan has been temporarily halted in the wake of the Fukushima incident, but permission to construct has not been withdrawn.

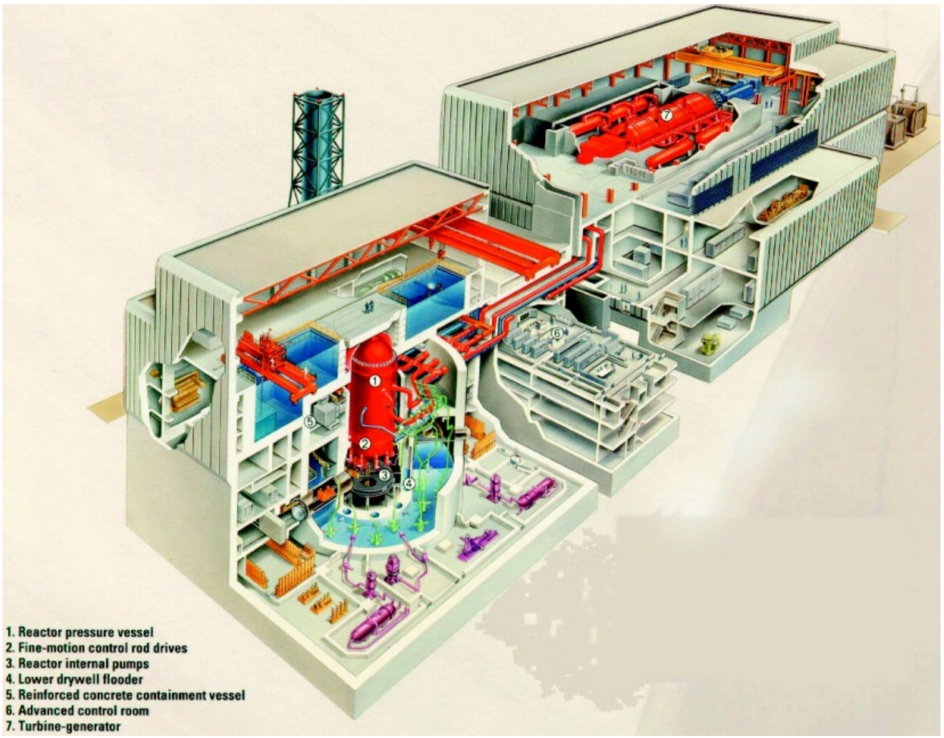

Figure 3-4: Advanced boiling water reactor (Source: University of Notre Dame [22])

- The advanced passive (AP) 1000: The AP 1000 offered by Westinghouse Electric Company is an evolutionary Generation III^{+} design based on the PWR design. It offers modular construction to reduce costs and construction time; passive safety systems that allow the plant to be passively cooled for 72 hours without any operator input; a simplified design and plant arrangement that compared with older PWRs uses 50 percent fewer safety-related valves, 80 percent less safety-related piping, 85 percent less control cable, 35 percent fewer pumps and 45 percent less seismic building volume (see Figure 3-5). With less infrastructure and equipment to maintain, it is expected that the AP 1000 will be safer and have lower operation and maintenance costs [13]. The power output of an AP 1000 reactor is 1,117 MW [14].

  Construction of four AP 1000 reactors is currently underway in China; they are expected to become operational in the years 2013-2015. In the U.S. the AP 1000 has been issued design certification by the NRC, and site preparations have begun for 4 units to be constructed in Georgia (Vogtle) and South Carolina (Summer). Additional applications have been submitted to the NRC for another 8 units [15].

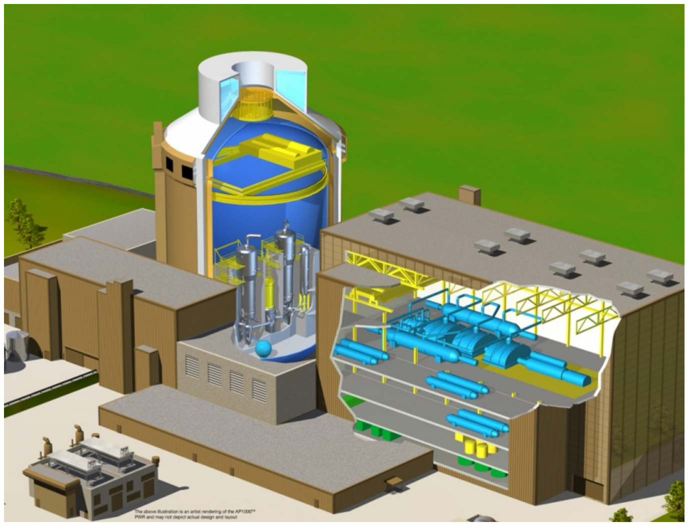

Figure 3-5: AP 1000 reactor (Source: Institute of Electrical and Electronics Engineers [23])

- The economic simplified boiling water reactor (ESBWR): The ESBWR offered by GE Hitachi Nuclear Energy is an evolutionary Generation III$^+$ nuclear reactor based on previous BWRs and the ABWR. It offers a simplified design and modular construction that reduces costs and construction time. The passive cooling natural circulation design eliminates 11 systems, and 25 percent of pumps, valves and motors compared with previous BWR designs. The expected power output is 1,520 MW with a capacity factor of 95 percent [16]. The ESBWR is currently being reviewed for certification by the NRC. There is currently one application submitted to the NRC for the construction of an ESBWR in Michigan [15].

- The U.S evolutionary power reactor (US EPR); The US EPR is offered by Areva Nuclear Power, and it is an evolutionary Generation III$^+$ PWR based on the French N4 model and the German Konvoi model. It features improved safety systems that include: 4 independent safety systems that are able to perform 100 percent of the safety function on their own, a leak tight containment structure to prevent radiation leaks, a retention area at the bottom of the reactor to prevent leaks in case of a core meltdown, and an outer shell capable of resisting a large aircraft impact. It also features increased efficiency through an axial economizer inside the steam generators and a heavy neutron reflector that lowers uranium consumption. The expected power output is 1,650 MW with a 92 percent capacity factor [17]. There are currently four US EPR reactors under construction, one in France, one in Finland and two in China. The reactors under construction in Finland and France have both experienced lengthy construction delays and cost overruns of over

50 percent; however it is expected that the reactors being built in China will benefit from the experience gained in France and Finland and therefore may incur lower costs and a shorter construction period [18]. The US EPR is currently under design certification review by the NRC, and there are currently two active applications in the U.S. for the construction of two US EPR units.

- The Mitsubishi advanced pressurized water reactor (US APWR): The US APWR is offered by Mitsubishi Heavy Industries, and it is a Generation III^+ PWR. It features advanced safety systems and improved reliability through the use of four independent safety systems, a neutron reflector, and steam generators with high corrosion resistance. It has an expected capacity of 1,700 MW [19]. The US APWR is currently under design certification review by the NRC, and there are two active applications in the US for the construction of three US APWR units.

3.4 Small modular reactors

Recently there has been growing interest around the world in small modular reactors which are defined as reactors that have electric power output of less than 300 MW. Small modular reactors offer several advantages over traditional nuclear power plants including: the ability to service small electricity grids; the ability to provide electricity to remote areas; and simpler, standardized designs that may reduce the cost of supplying nuclear power. They would be completely fabricated and assembled at a factory and shipped by truck or rail to be installed wherever they are needed. They can be operated independently or as modules that would be part of a bigger complex. Manufacturing economies of scale with higher production numbers are expected to help drive down the cost, making them a more accessible technology [24].

- NuScale reactor: The NuScale reactor, offered by NuScale Power Inc. is a modular integrated PWR based on the Multi-Application Small Light Water Reactor developed at Oregon State University. Each reactor module is integrated with its own steam generator in the same containment vessel, and each module has its own designated turbines for electricity generation (see Figure 3-6). The reactor containment structure would be submerged underground in a safety related pool. The concept is to have scalable NuScale power plants that can range from one to twelve reactors with each reactor operating independently from the others (see Figure 3-7). Each reactor has a capacity of 45 MW; therefore the power plants can range from 45 MW to 540 MW [25, 26]. This concept offers several advantages over traditional nuclear power plants including: lower costs because of factory manufacturing and assembly of reactor units, lower initial investment and project uncertainty because of incremental build, and the ability to increase capacity to match demand growth [27]. NuScale Power Inc. expects to submit an application for design certification in late 2012 [28].

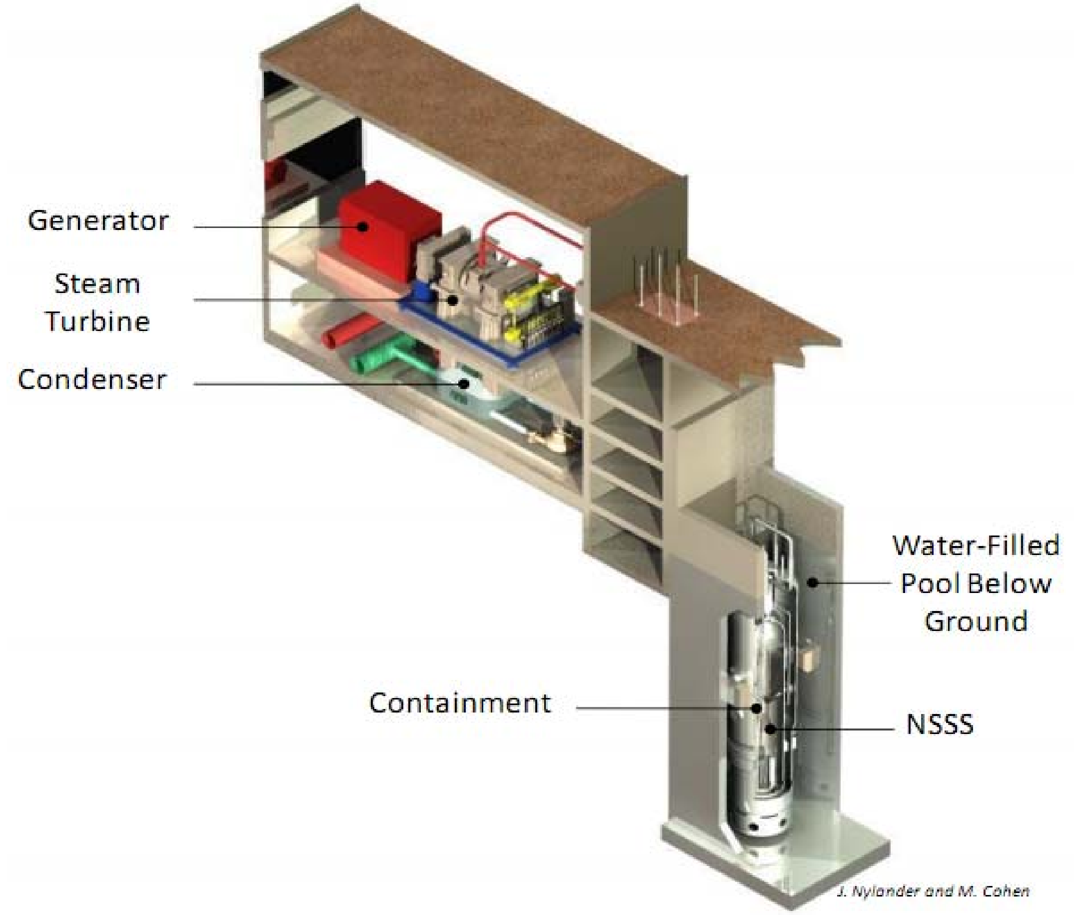

Figure 3-6: NuScale Reactor (Source: NuScale power [15])

Figure 3-7: NuScale multi-unit complex (Source: NuScale power [15])

- The Babcock & Wilcox mPower reactor: The mPower reactor is offered by the Babcock & Wilcox Company. It is an integrated PWR, with a modular design that allows for scalability in 160 MW increments. It features passive safety systems, underground containment and factory built reactors. Much like the NuScale reactor, the ability to be built incrementally would reduce construction time and some of the uncertainty related to the deployment of nuclear energy. Utility companies would have the ability to construct a unit, have it operating and generating revenue while at the same time expanding capacity at the plant. This would contribute to a reduction of front-end costs that could make nuclear energy a more attractive option [29]. It is expected that the Babcock and Wilcox Company will submit an application for design certification in the fourth quarter of 2013. TVA signed a letter of intent in June 2011 to purchase up to six mPower reactors [46].

- Toshiba 4S (Super Safe, Small and Simple): The 4S is being developed by Toshiba, the Central Research Institute of Electric Power Industry in Japan, the Lawrence Livermore National Laboratory and Westinghouse. The reactor design is a sodium cooled fast neutron reactor that features electromagnetic pumps and passive safety systems (see Figure 3-8). It has been dubbed the “nuclear battery” system because it requires refueling only every 30 years, has very low maintenance requirements and a power output of 10 MW. The reactor would be factory built and shipped out as a whole unit where it would be installed in an underground containment structure. Its features are appealing for use in remote locations for use in electricity generation and heat for industrial uses. In Alaska initial approval has been granted for the construction of a 4S unit in the remote town of Galena [30, 31]. Toshiba is expected to submit an application to the NRC for design certification in 2012.

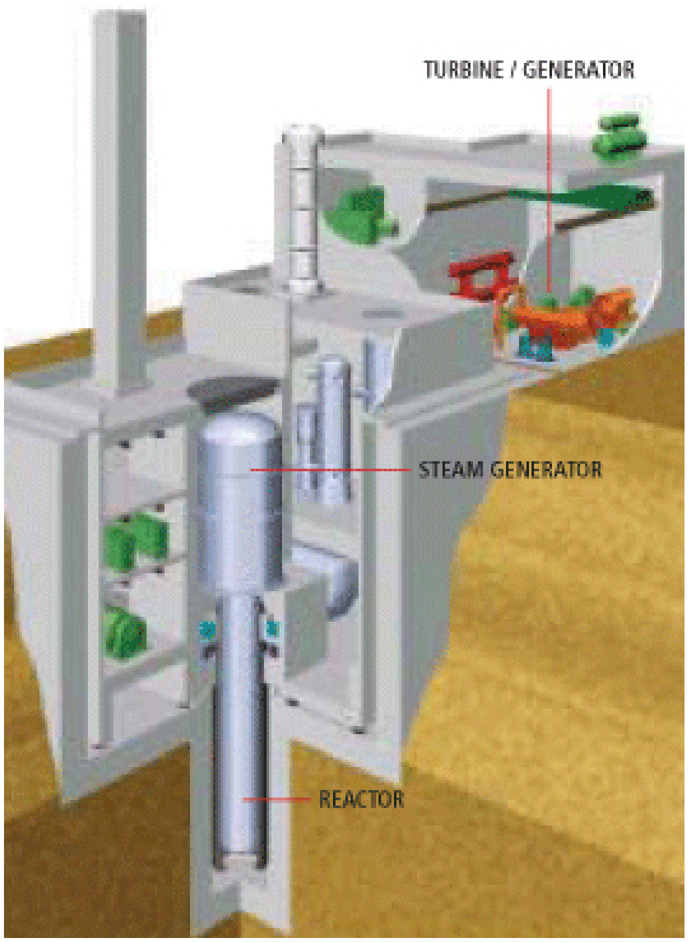

Figure 3-8: Toshiba 4S reactor (Source: Nuclear Street [39])

- Gen4 Module (G4M): The G4M previously named the Hyperion Power Module (HPM) is offered by the GEN_4 ENERGY. It is a similar concept to the Toshiba 4S reactor but uses a different technology (see Figure 3-9). It is a liquid metal cooled (Lead Bismuth Eutectic), uranium nitride fueled, fast reactor. The reactors would be factory built as standard, self-contained modules that would be easily transported by rail or truck. On site activities would only include the construction of the reactor vault and the non-nuclear systems, and the connection of the G4M to the non-nuclear systems and controls. The G4M has a 10 year fuel life-cycle, after which it would be replaced by a new module. It would have a 25 MW power output, making it ideal for remote locations and industrial processes [32]. GEN_4 ENERGY is expected to submit an application to the NRC for design certification and COL.

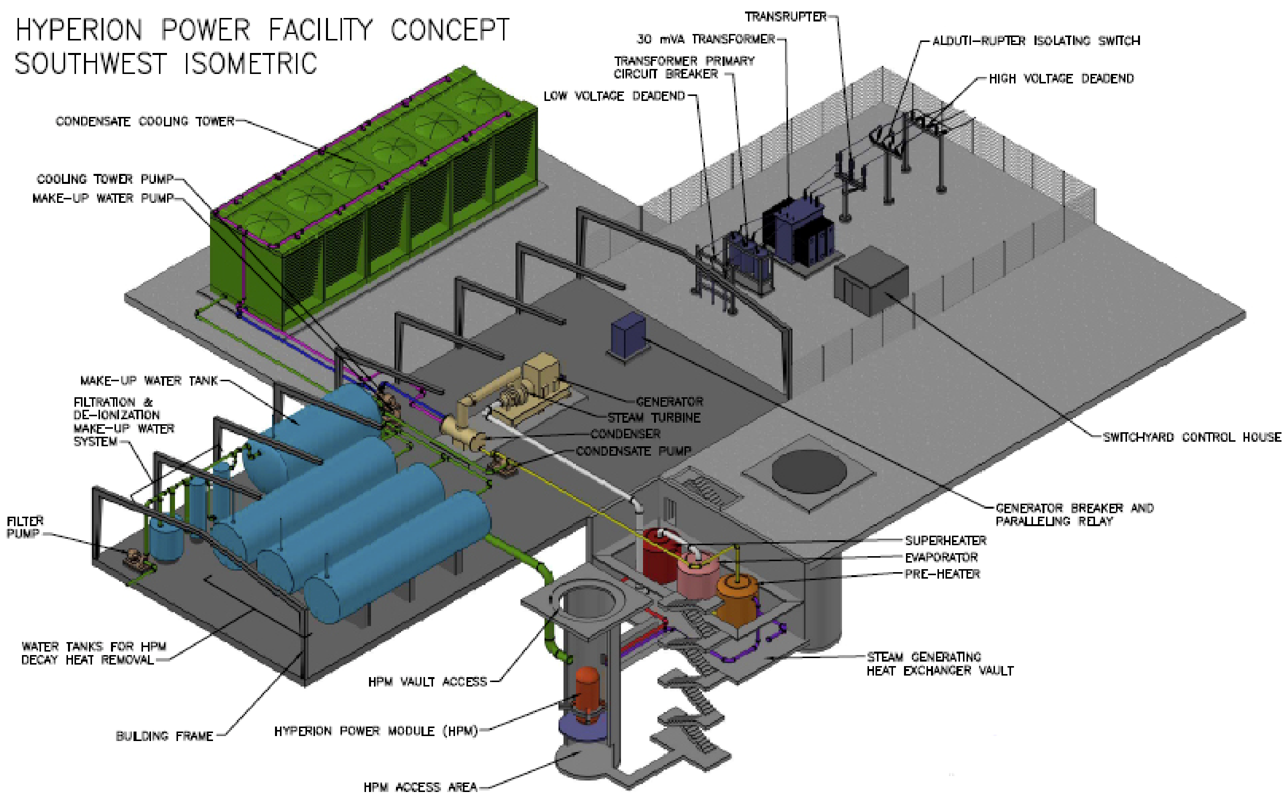

Figure 3-9: Hyperion power facility (Source: NRC [40])

- Westinghouse small modular reactor: The Westinghouse small modular reactor offered by Westinghouse Electric Company is an integrated reactor that features several safety systems and components of the AP 1000 reactor and a 225 MW power output. Westinghouse is expected to submit an application for design certification to the NRC in the near future [33].

- Power reactor innovative small module (PRISM) reactor: The PRISM reactor is being developed by GE Hitachi Nuclear Energy and several U.S. national laboratories. It is a sodium cooled, fast neutron reactor that would feature a modular design, passive safety systems and ground level containment. Each reactor would have a generating capacity of 311 MW and would be part of a two unit power block. The PRISM reactor could be fueled by plutonium that would come from spent fuel from light water reactors [34]. This makes them an appealing option because they contribute to a reduction of plutonium stockpiles that are expensive to store. GE Hitachi recently proposed the construction of a PRISM reactor in the United Kingdom as a way to deal with that country's plutonium stockpile [35]. There are also plans to construct a demonstration PRISM reactor at the Department of Energy's Savannah River site [36].

3.5 Generation IV reactors

Generation IV reactors are a set of theoretical revolutionary reactors that are being researched and developed under the Generation IV International Forum (GIF). GIF is an international agreement of 12 nations that are interested in cooperating in the development of Generation IV reactors. The forum is using eight goals that focus on the sustainability, economics, safety and reliability of future nuclear power generation. Generation IV reactors (see Figure 3-10) are expected to be safer, more sustainable, more economically competitive, are expected to have more applications for nuclear energy (such as hydrogen production) and will have new approaches to the management of nuclear materials in order to reduce nuclear waste [42].

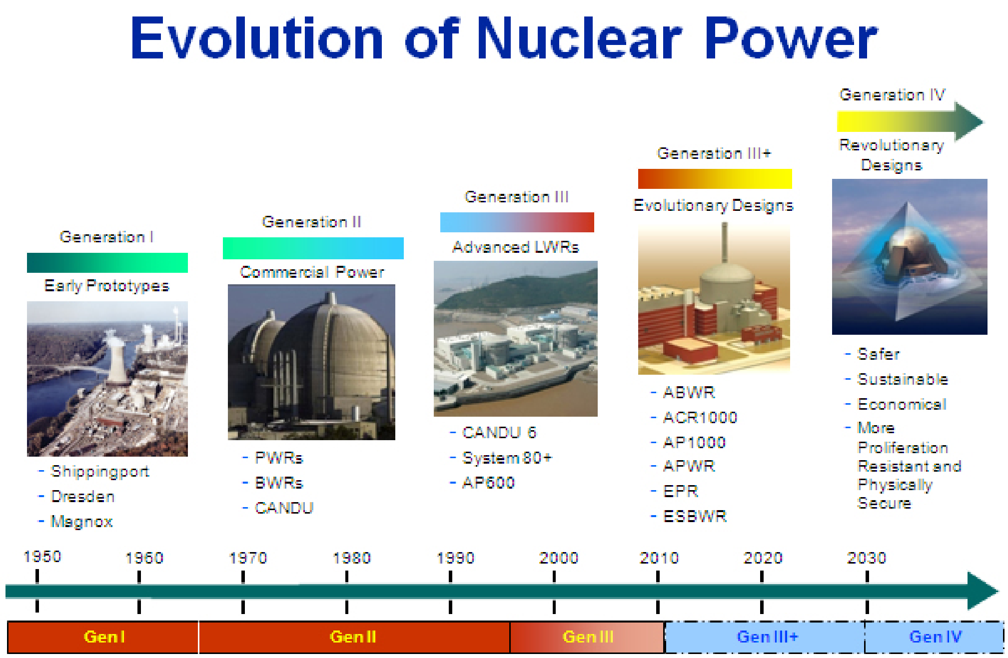

Figure 3-10: Evolution of nuclear power (Source: Generation IV international forum [45]

GIF identified six reactor designs with the greatest possibility to reach the performance goals. Research resources and collaboration are being focused on the six different reactors that encompass very different technologies and reactor sizes. The reactors are: the gas-cooled fast reactor, the lead-cooled fast reactor, the molten salt reactor, the sodium-cooled fast reactor, the super critical water cooled reactor, and the very high temperature reactor.

- Gas-cooled fast reactor (GFR): The GFR is designed to be a fast neutron reactor with a closed fuel cycle. In fast neutron reactors the nuclear chain reaction is sustained by fast neutrons, therefore there is no need for a neutron moderator; however because of this it needs a more enriched fuel [43]. Fuel reprocessing facilities would be onsite, reducing the need to transport nuclear materials. The GFR reactor would be helium-cooled and would have an expected output of 288 MW. It would be used for electricity and reduction in nuclear waste due to the reprocessing of fuel [44].

- Lead-cooled fast reactor (LFR): The LFR is a fast neutron reactor with a closed fuel cycle. It would use lead or lead/bismuth eutectic (a type of alloy) as coolant. The coolant choice increases the reactor's safety because of its inert nature. There are several options for the size of the reactor, from a 50 MW factory manufactured facility, to a 1,200 MW nuclear power plant. The LFR would be primarily used for electricity generation, hydrogen production, and nuclear waste management [44].

- Molten salt reactor (MSR): The MSR is a unique reactor design that, unlike all other designs, uses a liquid fuel made out of sodium, zirconium and uranium fluorides. The reactor can be configured to be either a thermal or fast reactor depending on the liquid fuel mixture. The MSR would have a closed fuel cycle, and because it uses a liquid fuel it does not require fuel fabrication. The plant is expected to have a 1,000 MW output. The MSR would be used for electricity generation and nuclear waste management [44].

- Sodium-cooled fast reactor (SFR): The SFR is a fast neutron, closed fuel cycle reactor. The liquid sodium coolant allows for high power density with a lower coolant volume fraction [43]. There are two sizes planned for the SFR; a 150 to 500 MW reactor, and a larger 500 to 1,500 MW reactor. The primary uses of the SFR would be electricity generation and nuclear waste management [44].

- Super critical water cooled reactor (SCWR): The SCWR is a high-temperature, high pressure, water-cooled reactor that operates above the critical point of water in order to achieve a greater thermal efficiency. The SCWR can be either a thermal neutron reactor with a once-through fuel cycle, or a fast neutron reactor with a closed fuel cycle. The expected output is 1,700 MW, and its primary use would be electricity generation [44].

- Very high temperature reactor (VHTR): The VHTR design is a thermal neutron reactor that uses helium gas as the coolant and graphite as the moderator. The VHTR would have coolant outlet temperatures above 1,000° C, which can be used to supply process heat for various non-electricity industrial activities including hydrogen production and coal gasification. VHTRs would primarily be used for the production of hydrogen and other heat intensive industrial processes; however electricity generation as part of a cogenerating plant is possible as well [44].

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4. Economics of Nuclear Power

The future of nuclear power depends on its ability to become a cost competitive source of electricity generation. It is an appealing source of generation because it has low fuel costs and no direct pollutants or greenhouse gas emissions. However a new nuclear power plant has much higher up-front capital costs than competing technologies that make the total generating cost of new nuclear higher than alternative sources such as coal and natural gas [1].

4.1 Costs of new nuclear power

In order to understand the economics of nuclear power it is important to understand its cost components and what factors affect them. The costs of generating nuclear power can be separated into three broad categories: capital costs, financing costs and operating costs.

Capital costs: Capital costs are the largest cost component of nuclear power and are typically quoted as overnight costs, indicating that financing costs have been excluded. Capital costs are comprised of several different costs including engineering-procurement-construction (EPC) costs; these are the costs of building the plant itself including physical plant equipment, materials and labor. This is the cost figure usually quoted by the reactor's vendor [2]. Owner's costs vary greatly depending on the construction site and include things such as land, cooling infrastructure, administration and associated buildings, site preparation, switch yards, project management, licenses, training staff and transmission infrastructure, among others [1]. Contingency costs are added by the vendors to cover any unexpected costs.[5] These may be negotiated and sometimes governments agree to pay these costs [2].

Historically, many nuclear (and other very large-scale infrastructure) projects have experienced significant cost overruns. Since no nuclear plants have been built in the U.S. for several years (Watts Bar Unit 1, whose construction began in 1972, was the last commercial unit in the U.S. to come online, it began commercial operation in 1996) the actual cost of building a nuclear power plant is unknown. The risk of cost overruns exists but the likelihood and magnitude are uncertain. In its August 2012 Semi-Annual Construction Monitoring Report to the Georgia Public Service Commission, Georgia Power reported that the most recent cost projection for construction of Vogtle Units 3 and 4 (AP 1000 units) was $92 million less than the original certification amount but acknowledged that the expected completion dates had been delayed by seven months due to Design Control Document approval delays at the NRC [14].

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[5] Historically, many nuclear (and other very large-scale infrastructure) projects have experienced significant cost overruns. Since there is no recent experience with nuclear construction in the U.S., the likelihood and potential magnitude is uncertain, but the risk of such overruns exists.

Table 4-1 is a compilation of the capital cost estimates that have been calculated by utilities on their specific projects for submission to regulatory authorities. It can be observed that for the same technology different utilities have quoted different capital cost estimates. This is because they were quoted in several different years ranging from 2005 to 2011. During that time period the cost of constructing a nuclear power plant has increased substantially. This is based on both observed construction costs from nuclear power plants built in Japan and Korea and cost projections for U.S. nuclear power plants. Additionally these numbers may be reporting different costs, because some utilities chose to include owner's cost while some did not. For example, the estimate for the Florida Power & Light total project cost includes the financing costs. Furthermore, it should be noted that costs for U.S. nuclear power plants built in the 1980s and 1990s were far higher than projected, and construction experienced long delays. Currently the constructions of an EPR in Finland and another in France have run into significant cost overruns and long construction delays [4].

Owner	Technology	Plant capacity (MW)	Overnight capital cost ($/kW) 2010	Total project cost (Billion $) 2010 dollars
SCE&G/Santee Cooper	AP 1000 2 units	2200[10]	4152[11]	9.27[11]
Florida Power & Light			3483-5063[10]	12.1 - 18[10]
Progress Energy			4611[11]	10.2[11]
Georgia Power			5202[11]	11.44[11]
NA		2236[12]	5339[12]	11.9[12]
Tennessee Valley Authority	ABWR	2835[13]	3212[11]	9.1[11]
NRG Energy		2660[11]	3815[11]	10.1[11]

Table 4-1: Compilation of capital cost estimates

Sources:
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Financing costs: Financing costs can vary greatly on a project by project basis and depend on several factors including: the interest rate on the debt, the risk premium, the debt-equity ratio, whether the retail electricity market in which the plant is located is regulated and the construction time. By the time a nuclear power plant starts generating electricity, financing cost can be as much as 25 to 80 percent of the overnight capital costs [2].

Operating costs: Nuclear power plants have lower variable operating costs as a result of lower fuel cost. Uranium fuel has a very high energy density (one kilogram of natural uranium will yield 20,000 times as much energy as one kilogram of coal); therefore it has much lower transportation cost than coal and natural gas [1]. Fixed operation and maintenance (O&M) costs include worker's wages, equipment maintenance costs, administrative expenses, etc. Variable O&M costs include the nuclear fuel and other consumable materials and supplies. Table 4-2 displays the O&M cost for nuclear and other sources of generation.

Technology	Nominal capacity (MW)	Fixed O&M cost (2010 $/kW)	Variable O&M cost (2010 $/MWh)	Overnight capital cost (2010 $/kW)
Nuclear				
	2,236	88.75	2.04	5,339
Coal				
Dual unit advanced PC	1,300	29.67	4.25	2,844
Dual unit advanced PC with CCS	1,300	63.21	9.05	4,579
Dual unit IGCC	1,200	48.90	6.87	3,221
Single unit IGCC with CCS	520	69.30	8.04	5,348
Natural Gas				
Conventional NGCC	540	14.39	3.43	978
Advanced NGCC	400	14.62	3.11	1,003
Advanced NGCC with CCS	340	30.25	6.45	2,060
Conventional combustion turbine	85	6.98	14.70	974
Advanced combustion turbine	210	6.70	9.87	665
Wind				
Onshore Wind	100	28.07	0.00	2,438
Solar				
Solar thermal	100	64.00	0.00	4,692
Large photovoltaic	150	16.70	0.00	4,755

Table 4-2: Operating and overnight capital costs for new sources of generation (Source: Energy Information Administration [3])

4.2 Economic competitiveness

When considering economic competitiveness, the distinction between existing nuclear power plants and new nuclear power plants must be made. Nuclear power plants that were built decades ago are highly cost competitive because their capital costs have largely been recovered. Variable costs, such as fuel and O&M, are relatively low for nuclear units when compared to fossil-fueled generators. New nuclear power plants on the other hand, are less competitive economically due to the high upfront costs. Currently the economic viability is affected by:

- High capital costs;

- Lengthy construction periods, because of interruptions by engineering and management problems, regulatory delays and public opposition;
- Market deregulation;
- Extended period of time without nuclear power plant constructions; and
- Relatively inexpensive electricity generated from other fuel sources.

Compared with other sources of generation, nuclear power has much higher capital costs that require large financial investments over a long period of time. This is due to the high degree of engineering complexity of nuclear power plants, numerous safety and security requirements for both the design and construction phases, and a lengthy licensing process [5]. Table 4-2 compares the overnight cost for AP 1000 reactors and other sources of generation.

The length of the construction period greatly affects the competitiveness of nuclear power because of the impact that it has on the financing costs. While the plant is under construction interest on the borrowed capital is being accrued. The longer the construction time and the more interruptions there are, the greater the interest cost that will have to be repaid once the plant starts generating electricity [2]. In order for nuclear power to be competitive, new nuclear plants will have to be built with tighter construction schedules.

Another factor that affects financing cost related to the construction uncertainty is the risk premium that nuclear projects face. The risk premium is a higher interest rate charged by the lenders to reflect the uncertainty associated with nuclear projects and the possibility that the nuclear power plant will not be completed or that the utility would not be able to repay the loan [2].

State regulations can also impact the overall cost of constructing nuclear plants. In a traditionally regulated state a utility company may be able to pass on some of the risk associated with construction to its consumers by getting pre-approval of some level of cost recovery. This may result in a lower risk premium for borrowing money and a lower overall cost. Furthermore, in states that have provision for recovery of construction work in progress (CWIP), the utility may be able to include some of the costs in its rates prior to project completion, thus reducing the total financing costs. In a deregulated market the merchant plant has to sell its power at the competitive prices. This places all of the financial risk on the investor creating uncertainty and discouraging long-term capital intensive projects [1].

Also, since there have been no major nuclear power projects in the U.S. for several years, the infrastructure for nuclear power plant construction has largely eroded. Thus, there are limited numbers of qualified engineers, suppliers for nuclear equipment and components, and contractors with the necessary skills and experience to construct a nuclear power plant. This shortage has the potential to increase the costs and length of construction.

- Levelized cost of electricity (LCOE): To facilitate a more direct comparison of the overall cost of various generating technologies, the LCOE is used. The LCOE represents the present value of the total costs of constructing and operating a power plant over its expected economic life, the costs are then annualized and expressed in real dollars to remove the impact of inflation. The LCOE is by no means a perfect measure because it often fails to account for whether a generator is dispatchable, makes several assumptions regarding aspects like unit capacity factor, and typically does not include things such as state or regional production incentives or regional fuel availability [3]. Table 4-3 displays the Energy Information Administration's estimated LCOE of new generating technologies entering service in 2016.

Plant type	Capacity factor (%)	Levelized capital cost	Fixed O&M	Variable O&M	Transmission investment	Total system levelized cost
Coal						
Conventional coal	85.0	65.3	3.9	24.3	1.2	94.8
Avanced coal	85.0	74.6	7.9	25.7	1.2	109.4
Avanced coal with CCS	85.0	92.7	9.2	33.1	1.2	136.2
Natural gas						
Conventional NGCC	87.0	17.5	1.9	45.6	1.2	66.1
Advanced NGCC	87.0	17.9	1.9	42.1	1.2	63.1
Advanced NGCC with CCS	87.0	34.6	3.9	49.6	1.2	89.3
Conventional combustion curbine	30.0	45.8	3.7	71.5	3.5	124.5
Advanced combustion turbine	30.0	31.6	5.5	62.9	3.5	103.5
Non-fossil fuel						
Nuclear	90.0	90.1	11.1	11.7	1.0	113.9
Wind	34.0	83.9	9.6	0.0	3.5	97.0
Solar thermal	18.0	259.4	46.6	0.0	5.8	311.8
Biomass	83.0	55.3	13.7	42.3	1.3	112.5
Hydro	52.0	74.5	3.8	6.3	1.9	86.4

Table 4-3: U.S. Average Levelized Costs (2009 $/MWh) for plants entering service in 2016
(Source: Energy Information Administration [6])

- Emissions costs: Nuclear power does not have any direct emissions of air pollutants that the U.S. Environmental Protection Agency (EPA) regulates, such as nitrogen oxides (NO_x), ozone (O_3), particulate matter (PM), and sulfur dioxide (SO_2). Additionally it does not directly emit greenhouse gases such as carbon dioxide (CO_2). Any regulation or initiative that would aim to decrease the emission of any of these pollutants or gases would change the generating cost for competing sources of generation. Natural gas and especially coal power plants would incur extra costs since these sources emit pollutants and greenhouse gases. On the other hand, nuclear, wind, solar and hydroelectric would not incur any extra costs because they have no emissions. Any tightening of restrictions on emissions would positively affect the economic competitiveness of nuclear power.

Recently the EPA approved two sets of regulations to limit the emission of pollutants by power plants. These are the Mercury and Air Toxics Standards (MATS) and the Cross-State Air Pollution Rule (CSAPR)[6]. In the state of Indiana it is projected that the implementation of these regulations, along with regulations affecting coal ash disposal and cooling water, would increase the price of electricity by 14 percent [7]. In the North Eastern U.S., 9 states participate in the regional greenhouse gas initiative (RGGI). It used to be 10 states but New Jersey pulled out as of January 1, 2012. The RGGI is a mandatory market based regulatory program to reduce greenhouse gas emissions. In this program, states auction CO_2 emission allowances to electric power plants that can then be traded to meet emissions controls. The proceeds of the auctions are invested in clean energy technologies [8]. The western climate initiative (WCI) is a similar initiative in the western states. In November, 2011, six western U.S. states withdrew from the WCI leaving only California and some Canadian provinces participating in the program [9]. The development of these types of regulations and initiatives may further reduce the economic disadvantage confronting nuclear power.

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5. Government Regulations and Incentives

The NRC is an independent government agency that is in charge of regulating all aspects of the U.S. civilian nuclear industry including commercial reactors, fuel processing facilities, and the transportation, disposal and storage of spent nuclear fuel for medical, academic and industrial uses.

5.1 Licensing

One of the main responsibilities of the NRC is the licensing of operating and proposed nuclear power plants. The licensing process involves a meticulous review of engineering, safety and environmental information, as well as numerous public hearings [1].

Every currently operating reactor was licensed in a two-step process where the licensee first submitted an application for a construction permit, and if approved, a second application for operation was submitted as the construction neared completion. This was typically a very lengthy and difficult process that created significant financial risk for the investors. As a response to the uncertainty that the licensing process created, the NRC developed a more simplified licensing process. Utilities now have the option to apply for a combined construction and operating license (COL). A COL authorizes construction of the nuclear plant and upon meeting pre-established NRC standards and without a final post-construction public hearing, the NRC would authorize the operation of the plant. The review for a COL takes 30 months if the application references a certified design, and if it references an uncertified design the review process takes 48 to 60 months. However there are many factors that can affect the schedule of the review process such as requests by NRC for additional information and the timely provision of that information by the applicant. Concurrently the NRC allows 12 months for the completion of a hearing process.

Utilities can also apply for an early site permit (ESP). An ESP allows a utility to obtain approval for a specific site without having to specify what reactor design it intends to build. This allows for the site specific safety, environmental and emergency preparedness details to be resolved regardless of the reactor built. The permit is valid for up to 20 years and it reduces site licensing uncertainty and siting issues before construction. Utilities that have already applied for a COL or an ESP can apply for a limited work authorization (LWA). LWA allow the applicants to perform certain limited construction activities at their site and at their own risk as they await a COL approval.

As another means to expedite construction, the NRC is also issuing design certifications. A design certification approves a standard power plant design independent of construction, operating or site licenses. Design certifications are valid for 15 years and can be renewed for an additional 15. In the design certification process the NRC reviews all the aspects of a complete nuclear power plant design at a generic site [2].

- Environmental review: As part of the licensing review process the NRC has to conduct a review of the environmental effects of the construction and operation of a nuclear power plant at a specific site. The NRC has to prepare an Environmental Impact Statement (EIS) in order to fulfill the NRC's responsibilities under the National Environmental Policy Act of 1969. The EIS is an analysis of the foreseeable effects that the proposed activity may incur on the environment, including the air, water, animal life, vegetation and natural resources, as well as any effect on any property that may have historic, archeological or architectural significance. The EIS must be done in a manner that is inclusive of all stakeholders, including the public, in order to determine what range of actions, alternatives and impacts are to be considered in the review. A draft EIS must be available for public review and comment. The NRC is required to respond to the comments and conduct further analysis if needed. A final draft includes a discussion of the comments made during the public review period.

- The EIS is done in cooperation with several other government agencies including the U.S. Army Corps of Engineers, U.S. Fish and Wildlife Service and the National Marine Fisheries Service. Additionally the EPA reviews the EIS for adequacy and makes comments during the EIS public review period.

  The environmental review also includes a Severe Accidents Mitigation Alternatives review and a decommissioning review. The Severe Accidents Mitigation Alternatives review is done to identify and evaluate possible changes that could improve safety performance and reduce the possibility of a severe accident; one that could cause damage to the reactor core with potential environmental impacts. Possible changes include hardware modifications and changes to procedures and the training program. The decommissioning review evaluates the costs and impacts of decommissioning a nuclear power plant. Decommissioning involves the safe removal of a nuclear power plant from service and the reduction of residual radioactivity at the site to permissible levels. Decommissioning costs vary greatly depending on the site but the minimum amount of funds required for reasonable assurance is $306 million for a pressurized water reactor and $390 million (2011 dollars) for a boiling water reactor [2].

- NRC safety review: The NRC must also conduct an operational safety review separate from the environmental review. The basis for the NRC's safety review is the Standard Review Plan (SRP) for review of safety analysis reports for nuclear power plants. The SRP is intended to assure quality and uniformity in all of the NRC's staff reviews and it makes information about regulatory matters available to members of the public and the nuclear power industry. The safety analysis report also specifies the NRC's acceptable level of safety for light-water reactor facilities.

For the safety review the NRC reviews a final safety analysis report submitted by the reactor applicant. This report includes detailed information about the design of the structures, systems and components of the proposed plant, and detailed data about the proposed site. Additionally it must discuss several hypothetical accident situations, safety features of the plants to prevent the accidents, and what could be done to mitigate the impact of an accident should one occur. It must also include information regarding the reactor and fuel design, radioactive waste management, radiation protection, accident analysis and quality assurance.

The safety review also includes security issues. After a license is granted the NRC periodically reviews, inspects and updates security issues at all of the operating plants. These reviews continue as long as the plant is operating. Any issues that are found are to be addressed immediately and changes are incorporated into the operating license. Since the terrorist attacks of 2001 the NRC has dedicated more attention to terrorist related matters including working in cooperation with the Department of Homeland Security. The NRC has imposed some enhanced security requirements and updated the security rules that apply to nuclear power plants [2].

- <u>State and local governments:</u> State and local governments also have an impact on nuclear power projects. Some states, such as California, have banned the construction of nuclear power plants. Local opposition in the state of Nevada to the Yucca Mountain nuclear waste repository led to the cancellation of the project.

5.2 Economic incentives

Given the financing challenges that capital intensive energy projects face, the Energy Policy Act of 2005 provided several economic incentives for the construction of nuclear power plants as well as support for advanced nuclear technology research. These incentives are meant to assist the first few utilities that commit to building a nuclear power plant and are not meant to support the nuclear power industry in the long term. The intention is that the first few constructed nuclear plants will demonstrate competitive economic performance and henceforth the industry can be self-sustaining. The incentives include:

- <u>Federal loan guarantees:</u> The federal government allotted 18.5 billion dollars in federal loan guarantees to cover 80 percent of a project's costs. Loan guarantees can significantly lower the financing cost for capital intensive projects. Because the federal government backs the loans, eliminating the risk premium, the utilities receiving the loans are able to get lower financing rates. Originally the DOE received 19 applications for 21 reactors for a total requested sum of $122 billion. Currently the DOE has only granted one $9 billion dollar loan guarantee for the Vogtle project in Georgia and is seeking further funding for other short-listed projects [1, 3].

- Production tax credits: A 2.1¢/kWh production tax credit is paid by the federal government for the first 6,000 MW of new nuclear capacity in the first 8 years of operation. This is comparable to the production tax credits given to renewable sources of generation. The credits are to be divided between the eligible facilities and are not to exceed $125 million per plant per year.

- Standby support: Standby support is a type of insurance that will cover the debt service (principal and interest) for regulatory delays, such as licensing and litigation issues. This program has $2 billion in funding and only the first six new plants are eligible [3].

Additional incentives included in the Energy Policy Act of 2005 are: the extension for 20 years of the Price Anderson Act for nuclear liability protection and $1.25 billion for the research and construction of an advanced high-temperature reactor. Additionally, the federal government provides funds for nuclear research at several U.S. national laboratories and universities.

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6. Safety

The safety record for nuclear power plants in the U.S. and around the world as compared with other sources of energy has been relatively good. A report by the Organization for Economic Co-operation and Development (OECD) summarized the number of severe accidents (those with more than 5 fatalities) and deaths resulting from those accidents in fossil, hydro, and nuclear energy chains from 1969 to 2000 (see Table 6-1). The energy chain refers to every stage of energy production including exploration, extraction, refining, storage, distribution and waste disposal. What the report found was that nuclear energy had much fewer accidents and deaths compared with the other major sources of energy.

	OECD		Non-OECD	
Energy chain	**Accidents**	**Fatalities**	**Accidents**	**Fatalities**
Coal	75	2,259	1,044	18,017
Oil	165	3,713	232	16,505
Natural gas	90	1,043	45	1,000
LPG	59	1,905	46	2,016
Hydro	1	14	10	29,924
Nuclear	-	-	1	31

Table 6-1: Summary of severe accidents (>5 fatalities) that occurred in fossil, hydro, and nuclear energy chains in the period 1969-2000 (Source: OECD)

Nuclear reactor accidents can be best described as low-probability but high-consequence risks. In the 50 year history of the civilian nuclear power industry and after 14,500 cumulative reactor years of commercial operation around the world, there have only been 3 major accidents. The greatest safety risk posed by nuclear power is an uncontrolled release of nuclear material that causes off-site contamination and radiation exposure [1]. Exposure to radiation poses a health risk through ionization, which is the process of adding or removing one or more electrons from atoms or molecules. Ionization can cause damage within a cell which can lead to cancer, genetic material mutation or more immediate physical harm [2]. As with any other industry, safety depends on proper planning, design with conservative margins and backup systems, the use of high quality components, and a well-established safety culture in operations [1].

6.1 Accident history

Since the 1950s, when reactors were first built, there have been several incidents of varying levels of severity at nuclear facilities all over the world. In order to communicate the significance of radiological events the International Nuclear and Radiological Event Scale (INES) was created by the International Atomic Energy Agency (IAEA) (see figure 6-1). The INES scale has seven levels; events on levels 1-3 are classified as "incidents", and events on levels 4-7 are classified as "accidents." To date there have only been 3 major accidents at commercial nuclear power plants. These are Three Mile Island in 1979, Chernobyl in 1986 and Fukushima in March 2011. Table 6-1 lists accidents at nuclear facilities that have been rated at an INES level of 4 or above.

GENERAL DESCRIPTION OF INES LEVELS			
INES Level	**People and Environment**	**Radiological Barriers and Control**	**Defence-in-Depth**
Major Accident Level 7	• Major release of radioactive material with widespread health and environmental effects requiring implementation of planned and extended countermeasures.		
Serious Accident Level 6	• Significant release of radioactive material likely to require implementation of planned countermeasures.		
Accident with Wider Consequences Level 5	• Limited release of radioactive material likely to require implementation of some planned countermeasures. • Several deaths from radiation.	• Severe damage to reactor core. • Release of large quantities of radioactive material within an installation with a high probability of significant public exposure. This could arise from a major criticality accident or fire.	
Accident with Local Consequences Level 4	• Minor release of radioactive material unlikely to result in implementation of planned countermeasures other than local food controls. • At least one death from radiation.	• Fuel melt or damage to fuel resulting in more than 0.1% release of core inventory. • Release of significant quantities of radioactive material within an installation with a high probability of significant public exposure.	
Serious Incident Level 3	• Exposure in excess of ten times the statutory annual limit for workers. • Non-lethal deterministic health effect (e.g., burns) from radiation.	• Exposure rates of more than 1 Sv/h in an operating area. • Severe contamination in an area not expected by design, with a low probability of significant public exposure.	• Near accident at a nuclear power plant with no safety provisions remaining. • Lost or stolen highly radioactive sealed source. • Misdelivered highly radioactive sealed source without adequate procedures in place to handle it.
Incident Level 2	• Exposure of a member of the public in excess of 10 mSv. • Exposure of a worker in excess of the statutory annual limits.	• Radiation levels in an operating area of more than 50 mSv/h. • Significant contamination within the facility into an area not expected by design.	• Significant failures in safety provisions but with no actual consequences. • Found highly radioactive sealed orphan source, device or transport package with safety provisions intact. • Inadequate packaging of a highly radioactive sealed source.
Anomaly Level 1			• Overexposure of a member of the public in excess of statutory annual limits. • Minor problems with safety components with significant defence-in-depth remaining. • Low activity lost or stolen radioactive source, device or transport package.

Figure 6-1: Description of INES levels (Source: IAEA [17])

Country	Facility	Type of facility	Year	INES level	Event description
Canada	Chalk river	Experimental reactor	1952	5	Core meltdown
United Kingdom	Windscale-1	Military reactor	1957	5	Release of radioactive material following a fire
Soviet Union	Kyshtym	Nuclear fuel reprocessing plant	1957	6	Significant release of radioactive material to the environment from the explosion of a waste tank
Czechoslovakia	Jasovské Bohunice	Commercial reactor	1977	4	Damage to fuel rods, corrosion damage, and release of radioactivity
USA	Three-Mile Island-2	Commercial reactor	1979	5	Severe damage to the reactor core
France	Saint Laurent-A2	Commercial reactor	1980	4	Fuel channel meltdown
Ukraine	Chernobyl-4	Commercial reactor	1986	7	Significant release of radioactive material due to explosion
Russia	tomsk	Nuclear fuel reprocessing plant	1993	4	Significant release of radioactive material due to explosion
Japan	Tokaimura	Nuclear fuel reprocessing plant	1999	4	Fatal overexposure to workers following an accidental criticality event
Japan	Fukushima 1-3	Commercial reactor	2011	7	Reactor explosion after loss of cooling

Table 6-2: Significant nuclear reactor accidents (Sources: WNA & the Guardian [1, 18]

- Three Mile Island (INES level 5): This accident occurred on March 28, 1979, in Middleton, Pennsylvania at the Three Mile Island site. It has been the most serious accident of a commercial nuclear power plant in the U.S., but it did not cause any deaths or injuries to any plant worker or member of the nearby community. The accident was caused by a combination of operator error, design deficiencies and component failures. The accident began as a relatively minor incident when one of the secondary coolant systems stopped working, causing the reactor to automatically shut down. The pressure in the primary coolant system began to increase and in order to prevent an excessive buildup, an automatic relief valve opened. It failed to close after a safe pressure level had been reached. Inadequate instrumentation in the control room did not allow operators to know that the valve was open and as a result coolant water drained out of the open valve. Lack of coolant caused the reactor to overheat leading to a partial meltdown of the reactor core.

There were small releases of radioactive gases that had authorities concerned about health impacts on the surrounding population. Several detailed studies about the radiological consequences of the accident by various agencies including the NRC, EPA, DOE, and several others, concluded that the exposure to radiation of the surrounding community was minimal – about one-sixth of the radiation that a person would get from a chest x-ray. Several different organizations and groups took thousands of samples of air, water, soil, vegetation, animals and foodstuff from the monitored area, but only very small levels of radiation could be attributed to releases from the accident. Despite severe damage to the reactor most of the radiation was contained and the actual releases had a negligible effect on individuals and the environment.

The Three Mile Island accident had a profound effect on both the U.S. nuclear industry and the way that the NRC operated. There were comprehensive changes regarding emergency response planning, reactor operator training, human factors engineering, radiation protection and several other areas of nuclear power plant operations. After a careful analysis of the accident the NRC drastically changed the way that it regulates its licensees. Regulations and oversight became broader and more robust and management of the plants has been more closely monitored [3].

- Chernobyl (INES level 7): On April 26, 1986, an accident occurred at the Chernobyl power plant in Ukraine, and it has been the only commercial nuclear power plant accident where radiation-related fatalities have occurred. The cause of the accident was related to specific design characteristics of the reactor, a RBMK-1000, which was only built in the Soviet eastern bloc. Two very important characteristics of this reactor significantly contributed to the accident. One was that it possessed what is known as a 'positive void coefficient', where an increase in steam bubbles (voids) inside the reactor core, causes increased reactivity (an increased amount of nuclear reactions). The other was that when the control rods were inserted into the reactor core, they temporarily caused an increase in reactivity.

  The day of the accident the operators were conducting a test to determine how long the turbines would continue to spin and supply power to the coolant pumps after a loss of main electrical power supply. After a series of improper operator actions and miscommunications between different staff workers, the reactor became very unstable. As the flow of the coolant water slowed down, caused by the run-down of the turbines that powered the pumps, steam started to build at the bottom of the reactor. Because of the positive void coefficient the reactivity of the reactor increased. Additionally when the operators inserted the control rods this had the effect of further increasing the reactivity of the reactor. The increased temperature caused fuel fragmentation and rapid steam generation, leading to an over pressurization of the reactor. The immense pressure caused the 1,000 ton cover plate of the reactor to become detached, jamming the half way inserted control rods and rupturing the fuel channels. This created even more steam which caused a steam explosion that dispersed nuclear material into the atmosphere followed by a second explosion that resulted from the buildup of hydrogen [4].

In order to put out the subsequent fires and prevent the further spread of nuclear materials, boron and sand were poured from helicopters flying above over top of the reactor. The reactor was then entombed in a concrete sarcophagus. Two workers were killed in the initial explosions and a further 28 people died, firemen and plant staff, in the following 3 months as the result of acute radiation poisoning. The accident released massive amounts of nuclear material over Russia, Belarus and Ukraine. It was estimated that about one million people could have been affected by the radiation. By the year 2000 about 4,000 cases of thyroid cancer had been diagnosed in children that had been exposed to the radiation. Because of rapid detection only a few turned out to be fatal. A Chernobyl Forum established by the IAEA in cooperation with several other UN organizations and the authorities in Russia, Belarus and Ukraine found that apart from the thyroid cancers, there was no evidence of other major public health impacts that could be attributed to the radiation [5].

Given that the design of the Chernobyl reactor was unique to the Soviet Union, the accident had little relevance to the nuclear industry outside of the Soviet Union. A report by the NRC regarding the implications of the Chernobyl accident on the U.S. nuclear industry found that no immediate changes were needed in the way that the NRC regulated both the design and operation of U.S. commercial nuclear reactors [6].

- <u>Fukushima (INES level 7):</u> On March 11, 2011 a 9.0-magnitude earthquake struck off the coast of Japan. There were 6 reactors at the Fukushima power plant. Units 4-6 were shut down for routine maintenance and refueling, and units 1-3 were in operation but automatically shut down, as designed, after the earthquake. After the earthquake the Fukushima power plant suffered a loss of power, at which point emergency on-site diesel generators turned on at all 6 reactors in order to provide power to the cooling systems. The generators provided power for about 40 minutes until a 45 foot tsunami struck the plant and inundated the site causing extensive damage to the site, including damage to the diesel generators. Due to the devastation caused by the tsunami in the area, off-site assistance to provide power for the pumps was not available. Only unit 6 retained a working generator that was used to operate the pumps to cool units 5 and 6. Units 1-4 did not have any power to operate the cooling pumps and as a result the reactor cores of units 1-3 melted. Due to hydrogen build up, there were explosions that released vast amounts of radioactive material in all 4 reactor buildings [7]. It took 3 weeks to bring the reactors into a stable condition, but it wasn't until mid-December 2011, that the reactors were officially in a 'cold shutdown' condition [8].

Since the Fukushima accident the NRC has been working to understand the events that happened in Japan in order to relay important information to U.S. nuclear power plant operators. A task force established by the NRC after the accident, concluded that there was no imminent risk to the continued operation of U.S. nuclear power plants, however it did make several recommendations regarding safety enhancements and emergency preparedness. [9].

6.2 Achieving safety

There are many ways in which the U.S nuclear industry strives to achieve high levels of safety. Everything from the design, siting, construction and operation of the power plants, as well as international collaboration contribute to the attainment of safety.

- Defense-in-Depth: Nuclear power plants in the U.S. and in western countries have an approach to design and operation to prevent and mitigate accidents known as Defense-in-Depth. The key to this approach is to create multiple independent and redundant safety systems in order to compensate for any human or mechanical error and to not rely exclusively on any single system. Features of this approach include access controls, physical barriers, redundant safety systems and emergency response measures [10].

- Safety features of reactors: The three safety functions that are to be performed with respect to the nuclear reactor itself are: the control of reactivity, the cooling of the fuel, and the containment of radioactive substances. To control the reactivity, control rods are inserted into the reactor core. These have neutron absorbing properties that decrease the number of nuclear reactions. Additionally, reactors are designed with inherent safety features that control the reactivity. For example, all western nuclear reactors are designed to have negative void coefficients. This means that if steam builds up in the coolant water, as a consequence of overheating, the nuclear reaction actually slows down. This occurs because in LWR the coolant water is also the moderator and as water evaporates there is a decrease in the moderating effect. For the cooling of the fuel all nuclear reactors have a back-up emergency core cooling system to remove excess heat in case of main coolant system power loss [1].

The containment of radioactive substances is one of the most important safety features that a nuclear reactor has. A typical power plant will have several barriers between radioactive material and the environment (see Figure 6-2). These include: the zirconium alloy tubes where the enriched uranium pellets are sealed to form the fuel rods; the reactor pressure vessel that can have walls up to 30 cm thick, depending on the type of reactor; and the reinforced concrete containment structure that has several compartments and walls up to 4 feet thick (see Figure 6-3). Containment structures can mitigate the severity of a nuclear accident as demonstrated by the Three Mile Island and Chernobyl accidents. In the Three Mile Island accident even though half of the reactor core melted, there was no significant release of radiation due to the adequacy of the containment structures. In contrast the Chernobyl reactor did not have containment structures comparable to the ones in western nuclear reactors [1].

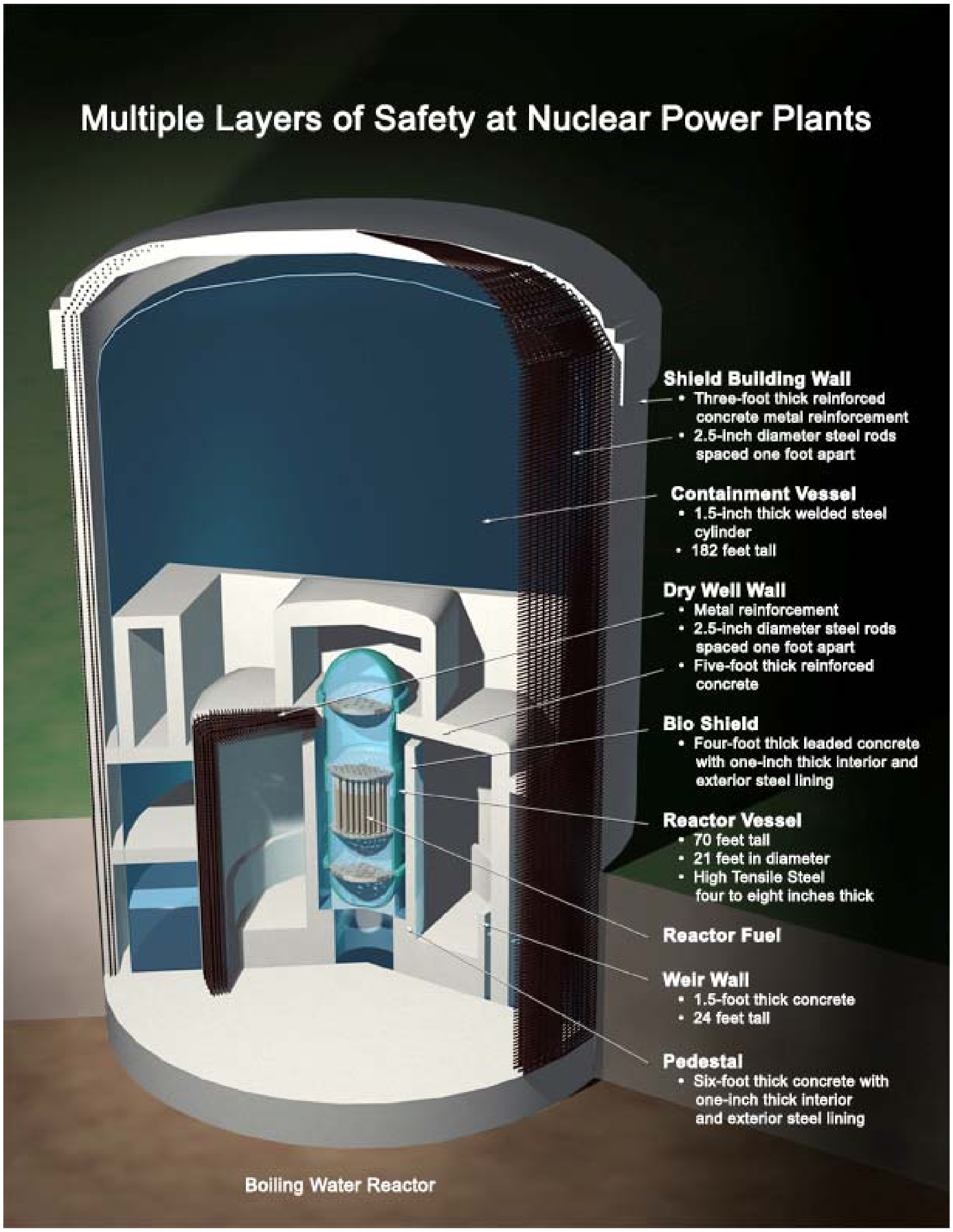

Figure 6-2: Safety barriers of a boiling water reactor (Source: Nuclear Energy Institute [16])

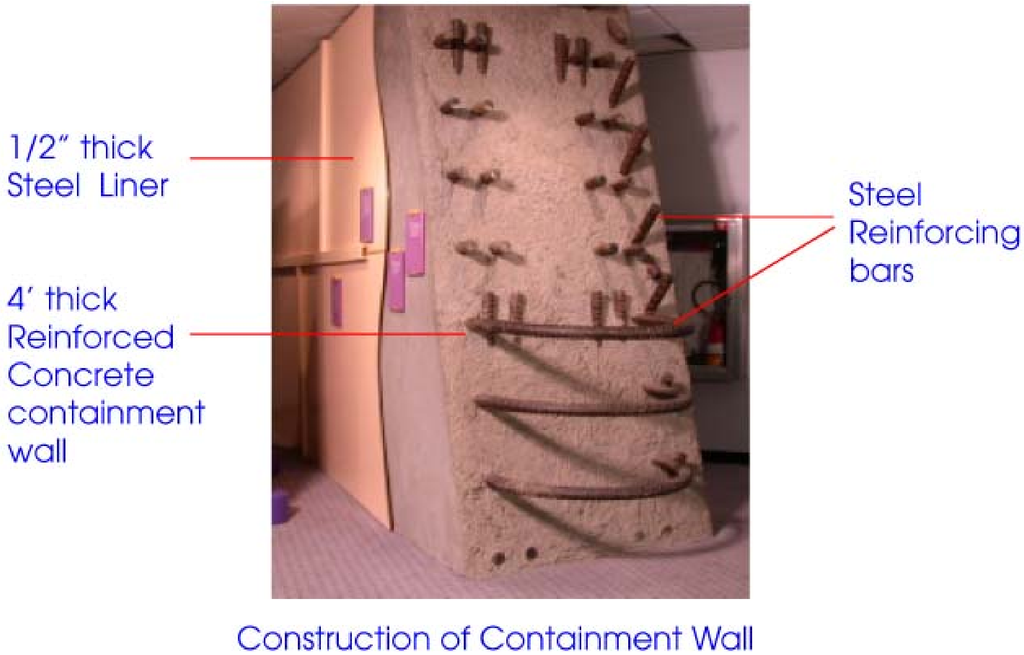

Figure 6-3: Construction of containment wall (Source: Nuclear Energy Institute [16])

Most of the safety systems on currently operating reactors are 'active' safety systems in the sense that they require mechanical or electrical operation in order to work. In the new reactor designs, Generation III and III$^+$, several active safety systems have been replaced with passive systems. Passive safety systems depend only on physical phenomena such as gravity, convection and resistance to high temperature to function.

6.3 Siting

Several safety and design considerations have to be taken into account when choosing the site to build a nuclear power plant. Because of cooling requirements nuclear power plants are usually built close to bodies of water. This places the plants at risk of being flooded by storms, tides and tsunamis. During the site licensing process worst case scenarios are considered in order to build proper safety barriers, however there have been several instances where flooding occurred at nuclear power plants. This can have catastrophic consequences as demonstrated by the Fukushima accident where the flooding of the back-up generators caused a meltdown in 3 reactor units [1].

Another important siting consideration is whether the site is in an area of significant seismic activity: 20 percent of the world's reactors are located in areas of significant seismic activity. Reactors in these areas have more stringent criteria for planning, design and construction in order to withstand very strong earthquakes. All reactors are designed to automatically shut off in case a major seismic event. After the March 2011 earthquake off the coast of Japan, 11 operating nuclear reactors automatically shut off [11]. Similarly, the North Anna, VA nuclear plant shut down due to the August 2011 earthquake.

6.4 Industry organizations

The Institute of Nuclear Power Operations (INPO) was established in 1979 following the recommendation of the Kemeny Commission, which was set up by President Carter to investigate the Three Mile Island accident. INPO's mission is to promote high levels of safety and reliability in the operation of nuclear power plants by establishing performance objectives, conducting regular detailed evaluations of nuclear power plants, and by providing assistance to nuclear power plant operators [12].

6.5 International cooperation

There is a great deal of international cooperation with regards to the safe operation of nuclear power plants. Following the Chernobyl accident the World Association of Nuclear Operators (WANO) was set up in 1989. There is evidence that many accidents could have been prevented had information learned from previous incidents been shared. WANO helps operators to easily communicate and share operational experience and information. WANO has helped achieve high levels of safety worldwide through its four main programs: peer reviews, operational experience, technical support and exchange, and professional and technical development [13]. At the end of 2009 all of the world's commercial power plants had been peer-reviewed at least once [1].

The IAEA's Convention on Nuclear Safety (CNS) is another instrument by which international nuclear safety is strengthened. The Convention came into effect in 1996 with the aim to legally commit participating states operating land-based nuclear power plants to maintain a high level of safety by setting international benchmarks to which states would subscribe. Currently there are 72 contracting parties including all countries that operate nuclear power plants [14]. The NRC prepares a U.S. National Report every three years for the CNS and assigns experienced technical managers to participate in peer reviewed discussions [15].

6.6 Terrorism

Ever since the September 11, 2001 terrorist attacks in the U.S., there has been much concern about the possibility of an aircraft being used by terrorists to impact a nuclear facility with the intention of releasing radioactive material. Several studies including one by the Electric Power Research Institute paid for by the DOE concluded that reactor structures were more than strong enough to resist the impact of a large aircraft. Separate computer analysis models were used to simulate a fully-fuelled Boeing 767-400 striking the reactor structure, used fuel storage pools and dry storage facilities. The model showed that no part of the aircraft or jet fuel penetrated any of the containment structures. Nonetheless since 2001 it is estimated that nuclear operators have spent over $2 billion in NRC required security improvements such as new barriers, bullet proof security stations and other physical modifications [1].

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7. Decommissioning

As part of the conditions for receiving an operating license, the NRC requires that the licensee make provision for the decommissioning of the nuclear power plant after it permanently ceases operations. Decommissioning is the safe removal of a facility from service and the reduction of residual radioactivity to levels that allow the termination of the NRC license. Decommissioning involves removing the spent fuel, dismantling any systems and components containing activation products (such as reactor vessel and primary loop), and cleaning up and dismantling any contaminated materials. All activated materials have to be shipped off-site to a waste processing, storage or disposal facility. Contaminated materials may be either cleaned of contamination or shipped off-site.

7.1 Decommissioning process

The decommissioning of a nuclear power plant is a long and expensive process that involves the following major steps:

- <u>Notification:</u> After an operator decides to permanently cease operation it must inform the NRC in writing the exact day when it plans to do so. The operator must also inform the NRC when it has permanently removed the fuel from the reactor vessel.

- <u>Post-shutdown decommissioning activities report (PSDAR):</u> Before or within two years following the cessation of operations the operator must submit a PSDAR to the NRC. A PSDAR includes a description of the decommissioning activities, a schedule for the accomplishment of such activities, an estimate of the expected costs, and document that the environmental impacts associated with the decommissioning activities fall within the previously submitted environmental impact statement. Upon receipt the NRC will make notice of the receipt in the federal register and make the PSDAR available for public comment. In addition, the NRC holds a public meeting near the decommissioning site for discussion of the PSDAR. The licensee can begin decommissioning activities 90 days after the PDSAR submission. Decommissioning must take place within 60 years after cessation of operations unless otherwise permitted by the NRC. The licensee remains completely accountable until the NRC terminates its license.

- <u>License termination plan (LTP):</u> Two years before the termination date a licensee must submit a LTP describing: site characterization, identification of remaining dismantling activities, plan for site remediation, plans for final survey of residual contamination on the site, a description of the end-use of the site, an updated estimate of the remaining costs, and a supplemental environmental report. Upon receipt of the LTP the NRC makes the plan available for public comment and holds a public meeting near the decommissioning site. The NRC reviews the LTP, and if everything is in accordance with NRC's regulations it approves the plan.

- Completion of decommission: At the conclusion of decommissioning activities the licensee has to submit a final radiation survey report. The NRC will terminate the license if it determines that the dismantling was performed in accordance to the LTP, and that the final radiation demonstrates that the facility and site are suitable for release. If the site is released for unrestricted use, any use of the site is permitted including restoring the natural habitat, farming, or continued industrial use.

7.2 Decommissioning costs

The decommissioning process is expensive; the NRC estimates that the costs of decommissioning a nuclear power plant are in the range of $280 to $612 million. The total cost depends on many factors including the sequence and timing of the various stages of the program, location of the facility, radioactive waste burial costs, and plans for spent fuel storage. The NRC ensures that the licensee will be able to pay for the decommissioning cost through three different means: prepayment, external sinking fund or surety method or insurance.

- Prepayment: At the start of operations the licensee deposits into an account the funds necessary to pay for the decommissioning costs. This account is not to be under the licensee's control. Forms of prepayment include an escrow account, trust, government fund, certificate of deposit, or deposit of government securities.

- External sinking fund: The external sinking fund is established and maintained by setting funds aside periodically in an account outside of the licensee's control. The funds have to be sufficient for the decommissioning costs at the anticipated time when the plant goes out of service. The sinking fund may be in the form of a trust, certificate of deposit, escrow account, government fund or deposit of government securities.

- Surety method or insurance: The surety method may be in the form of a surety bond, letter of credit or line of credit. Any surety method or insurance must be open ended, provide the full face amount, payable to a trust fund established for decommissioning costs and remain in effect until the commission has terminated the license.

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