NUCLEAR REACTOR OVERVIEW AND REACTOR CYCLES.

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Contents

Glossary

ACR	Advanced CANDU Reactor
ADS	Accelerator Driven System
AECL	Atomic Energy of Canada Ltd.
AGR	Advanced Gas-Cooled Reactor
BNFL	British Nuclear Fuels
BWR	Boiling Water Reactor
CANDU	CANadian Deuterium (natural) Uranium
DU	Depleted Uranium
ECC	Emergency Core Cooling
FBR	Fast Breeder Reactor
GCR	Gas Cooled Reactor
HEU	High Enriched Uranium: greater than 20 percent uranium-235
HWLWR	Heavy Water, Light Water Reactor
IAEA	International Atomic Energy Agency
ITER	International Thermonuclear Experimental Reactor
JET	Joint European Torus - fusion experiment
k	Reactivity: the neutron multiplication factor relating the number of neutrons which go on to produce fission, relative to the number of neutrons producing fission in the immediately preceding generation. If 'k' is one, then the same number of neutrons produce fissioning in each generation.
kt	kilotons of TNT equivalent. Explosive yield of a nuclear weapon.
LEU	Low Enriched Uranium: less than 20 percent uranium-235
LMFBR	Liquid Metal Fast Breeder Reactor
LPECI	Low Pressure Emergency Core (Cooling) Injection

LWGR	Light Water Graphite Reactor
Megawatt	One million watts
MeV	Million electron volts
MJ	mega joules of energy: 1E6 joules
MOX	Mixed Oxide Fuel: uranium, plutonium
MSRE	Molten Salt Reactor Experiment
MWd T^{-1}	Megawatt Days per Tonne of nuclear fuel
MW(e)	Megawatt (electrical)
NNPT	Nuclear Non-Proliferation Treaty
OECD	Organization for Economic Co-operation and Development
ORNL	Oak Ridge National Laboratory
PWR	Pressurized Water Reactor
RBMK	Russian Graphite Moderated Reactor - Chernobyl type
SNM	Special Nuclear Materials: plutonium, uranium-233 and uranium-235
TBq	Terabecquerel, 1E12 Bq
Terawatt	1E12 Watts
TU	Transuranium - above uranium
VVER	Russian PWR
WNA	World Nuclear Association
Z	Atomic number. The number of protons in an atom.

Summary

This article provides a broad overview of most of the known nuclear reactors: natural reactors of the past and present, and research, naval and commercial reactors operating in the world today. It traces some of the history of the main milestones in nuclear discoveries over the last 200 and more years, leading initially to the race to develop the first nuclear weapons and then to develop nuclear reactors for naval use and then for commercial and other uses, all of which were developed in the last 60 years. There is brief consideration of nuclear reactions which make nuclear power possible, and of the various fissile and fertile nuclear fuels that were discovered and produced to become available for use in weapons and then for production and use in different reactors and reactor cycles. It briefly examines the origins of nuclear energy from the cosmological beginnings of the universe and the operation of our own sun, through the earliest known terrestrial nuclear reactor, which operated 1.8 billion years ago in Africa. It presents a brief description of the construction and operation of the first controlled fission reactor (CP-1) developed and constructed by Enrico Fermi in Chicago in 1942. It looks briefly at the major reactor types operating in the world today, with some consideration of possible future reactor types and operation, including the Fast Breeder Reactor (FBR), the thorium breeder reactor, Accelerator Driven reactor Systems (ADS) and fusion energy. It introduces the major features of the common reactor operating cycles along with their advantages and disadvantages from the point of view of spent fuel reprocessing, weapons destruction, radioactive waste disposal volumes and fuel reserve outlook, which can be extended to millions of years with the various breeder cycles.

1. NUCLEAR REACTORS AND AN OVERVIEW OF NUCLEAR HISTORY

1.1 World Reactors

There are about 1100 to 1400 reactors of various types and sizes in operation throughout the world in almost 80 countries:

- There are 443 large operating commercial nuclear reactors (January 2003), with another 30 reactors under construction and a further 30 in various stages of design spread through 35 countries. They range from about 400 to 1200 megawatts in electrical energy output. They use either Low Enriched Uranium (LEU <20 percent uranium-235) enriched up to about 3 to 4 percent, or natural uranium (0.7 percent uranium-235). Others are refueled with recycled uranium and plutonium as mixed oxide (MOX) fuel from reprocessing, or from retired nuclear weapons. Typical fuel requirements are from about 20 to 100 tonnes for each year or more of operation of each reactor. The spent fuel discharged from all 443 of these commercial reactors amounts to a world total of about 15,000 tonnes annually. This total world tonnage for a year is less than a single day's ore output from many metal mines and quarries, which can approach an output of 50,000 tonnes and more of ore per day.

- About 400 (or possibly about 700 according to a French report, and including various reactors not disclosed for reasons of military security) are smaller marine propulsion reactors used in nuclear powered ships (aircraft carriers and icebreakers, with multiple reactors) and submarines (U.S. (75), Russia (50), U.K. (15), France (10), and China (unknown)) with usually one but sometimes more than one reactor, using High Enriched Uranium (HEU >20 percent uranium-235). Naval reactors are designed at the present time to operate for the life of the vessel - possibly 30 years - without requiring a fuel change. Earlier designs used less enriched fuel, and required several core changes over the life of the vessel. The spent fuel from all of these, as they are re-fitted or retired, amounts to no more than a few tens of tonnes in a year. Not included are several small nuclear reactors that were constructed for use in space probes destined for long-term missions beyond the solar system, and others where the unreliability and expense of solar collection systems could not be tolerated.

- About 290 small operating reactors, from a total of about 450 currently listed by the IAEA, are mostly relatively small research reactors operating in about 60 countries. These include 60 'zero power' critical assemblies, 23 test reactors, 37 training facilities, two prototypes, and one producing electricity. The potential power output ranges from a few kilowatts up to a few tens of megawatts of thermal energy using relatively small quantities of LEU or HEU fuel. Many are under-utilized and are used only intermittently. A few exceed 100 megawatts. Most are used for nuclear research, including Fast Breeder applications (the larger reactors). Some are almost fully utilized to produce medical radionuclides for use in Nuclear Medicine departments in most large hospitals around the world, as well as for other industrial applications. The spent fuel from nearly all of these amounts to no more than a few tonnes each year.

Other uses of nuclear reactors are in use or being considered. These include desalination projects to produce potable water in the middle and far east; district heating (especially in the states of the former U.S.S.R.); to provide steam to the petroleum industry for refining and to assist in oil extraction in situ from certain oil reservoirs and tar sand deposits in Canada; and barge-carried small reactors to provide electricity to remote, navigable locations (U.S. Panama Canal Zone from 1968 to 1975 for grid supply, and Russia).

There are in excess of about 3000 nuclear facilities of various kinds in operation throughout the world not counting departments of Nuclear Medicine in hospitals. All of these are based upon the operation of many of these reactors and their products. They contribute directly to society's needs in medical and industrial isotope production, industrial research, and to numerous agricultural and industrial, as well as social applications of radionuclides.

1.2 Nuclear History Milestones

Although the ancient Greeks coined the word 'atom', they had no means of understanding anything about atoms, other than that Democritus seems to have defined them to be the smallest subdivision of any matter that retained all of the properties of the original material. They knew nothing of neutrons, protons or electrons, nor of radiation or nuclear energy. This state of knowledge did not change significantly until the various discoveries concerning radiation and radioactive emissions after 1895 began to raise questions about the nature and significance of the atomic structure. Some of the key milestones in understanding the component parts of atoms and how they interact and behave or can be induced to behave, either for destructive purposes or for the very great benefit of humankind, as with any technology, are shown in Table 1.

Table 1. Nuclear History Selected Milestones	
Year	**Event**
-12E9	The Big Bang and cosmological evolution
-2E9	The Oklo Reactors, Gabon, Africa
1789	Klaproth isolated uranium from uranium ore
1829	Berzelius isolated thorium.
1895	Wilhelm Konrad Roentgen at the University of Wurzburg discovered X-rays in his vacuum tube experiments, and took the first X-ray photograph; that of his wife's hand
1896	Henri Becquerel (at the Museum of Natural History in Paris) discovered radioactivity in a piece of uranium ore left sitting upon a photographic film in a draw. Marie and Pierre Curie went on to investigate radioactivity, and isolated radium and polonium from Joachimstal uranium ore
1898	J.J. Thomson detected the emission of electrons when a metal surface is illuminated by ultraviolet light - the photoelectric effect
1905	Einstein formulated his Special Theory of Relativity, one aspect of which (the equivalence of mass and energy) began to give some insight into the origin of the atomic energy that had been revealed by the discovery of radioactive decay
1911	Rutherford published his conclusions drawn from alpha scattering experiments - that nearly all of the mass of the atom is concentrated in a tiny positively charged region in the center called the nucleus.
1912	J.J. Thomson discovered isotopes of neon, showing that atoms of the same element could have different masses.
1913	Niels Bohr devised the "Bohr atom" - a planetary model of the hydrogen atom with the electron orbiting the positively charged nucleus - that explained the characteristic spectral emissions from the hydrogen atom.
1920	Ernest Rutherford speculated on the possible existence and properties of the neutron.
1932	James Chadwick conclusively demonstrated the existence of neutrons.
1932	Cockroft and Walton in the UK were the first to split an atom.
1933	Hungarian physicist Leo Szilard had the idea of using a chain reaction of neutron collisions with atomic nuclei to release energy. He also considered the possibility of using this chain reaction to make bombs.
1934	Szilard filed a patent application for the atomic bomb. In his application. Szilard described not only the basic concept of using neutron-induced chain reactions to create explosions, but also the key concept of critical mass. This patent made Leo Szilard the inventor of the atomic bomb.
1934	Fermi's research group achieved uranium fission, but did not recognize it. Several radioactive products were detected, but positive identifications were not made. Interpreting the results of neutron bombardment of uranium became known as the "Uranium Problem". He also discovered the principle of neutron moderation, and the enhanced capture of slow neutrons.
1938	Hahn and Strassmann were confused over the results of an experiment which actually achieved fission, but which they did not recognize. Hahn contacted Lise Meitner who recognized that they had achieved fission, and relayed her interpretation to Hahn.
1938	Hahn determined conclusively that one of the mysterious radioactive substances was a previously known isotope of barium, which had arisen by fission. Working with Meitner, they developed a theoretical interpretation of this demonstrated fact.
1939	Otto Frisch observed fission when he detected fission fragments in an ionization chamber. Niels Bohr publicly announced the discovery of fission, at a conference in Washington D.C. He also realized that U-235 and U-238 had different fission properties, and that the undiscovered element 94-239 (plutonium-239) was also fissile. The fact that a large cross section for slow fission implied a large fast fission cross section (for weapons) was only later realized. Szilard, Teller and Wigner feared that the fission energy might be used in bombs built by the Germans. They persuaded Albert Einstein, America's most famous physicist, to warn President Roosevelt of this danger, which he did in an August 2, letter. Werner Heisenberg was actually trying to develop such a weapon for Germany, but received inadequate support. Szilard wrote to Fermi and described the idea of a uranium lattice in carbon, as a chain reactor.
1940	John Dunning at Columbia made the first direct measurements of the slow fission cross-section of

	U-235. George Kistiakowski suggested gaseous diffusion to produce quantities of U-235.
1941	In February 1941, Abelson began actual development of a practical uranium enrichment system (liquid thermal diffusion) and on February 26, Seaborg and Wahl discovered element 94 - plutonium. By July 1941 plutonium was demonstrated to be a much superior fissile material than U-235. Fermi and his team at Columbia assembled a sub-critical pile of 30 tonnes of graphite and 8 tonnes of uranium, with a projected k (neutron multiplication factor) of 0.83. Purer materials were obviously needed to get k above 1; the 'critical' point.
1942	A new district organization was created with the intentionally misleading name "Manhattan Engineer District" (MED), now commonly referred to as "The Manhattan Project".
1942	Fermi's first experimental pile in Stagg field had a projected k of 0.995. On December 1, 1942, Fermi's group completed CP-1 in a squash court at Stagg Field, Chicago. On December 2, CP-1 went super-critical (became more than self-sustaining) with k=1.0006, and reached a thermal output of 0.5 watts, before being closed down.
1945	July 16 1945 - At about 5:30 a.m. Gadget (Pu-239) was detonated in the first atomic explosion in history at the Trinity site. The explosive yield was 20-22 kt (kilo-tonnes of TNT equivalent), vaporizing the steel tower. One military observer had opined just prior to the explosion that it would likely be a squib.
1945	August 6, 1945 - 8:16 (Hiroshima time) Little Boy (U-235) exploded at an altitude of 1850 feet, 550 feet from the aim point, the Aioi Bridge, with a yield of 12.5-18 kt (best estimate was 15 kt).
1945	August 9, 1945 - 11:02 (Nagasaki time) Fat Man (Pu-239) exploded at 1950 feet near the perimeter of the city, scoring a direct hit on the Mitsubishi Steel and Arms Works. The torpedoes that were used against Pearl Harbor in 1941, starting the US conflict with Japan, were made in this Nagasaki factory. The yield was 19-23 kt (the best estimate was 21 kt).
1951	The first nuclear reactor to produce electricity (about 100 watts) was the small Experimental Breeder reactor (EBR-1) in Idaho, which started up in December 1951. The main U.S. effort in reactors at that time was under Admiral Hyman Rickover, who developed the Pressurized Water Reactor (PWR) for naval use.
1953	The Mark 1 prototype naval reactor started up in Idaho.
1954	The first nuclear-powered submarine, *USS Nautilus*, was launched.
1954	A prototype graphite moderated but water-cooled reactor, Obninsk, the world's first commercial nuclear power plant, started up in Russia.
1956	In Britain, the first of the 50 MW(e) Magnox reactors, Calder Hall-1, started up.
1957	The U.S. Atomic Energy Commission built the 90 MW(e) Shippingport demonstration PWR reactor - a modified submarine reactor design - in Pennsylvania. It operated until 1982.
1959	The U.S.A. and U.S.S.R. launched their first nuclear-powered surface vessels.
1960	In the U.S.A., the boiling water reactor (BWR) was developed by the Argonne National Laboratory, and the first one, Dresden-1 of 250 MW(e), designed by General Electric, was started up. Westinghouse designed the first fully commercial PWR of 250 MW(e), Yankee Rowe, Massachusetts, which started up in 1960 and operated to 1992.
1977	Starting in 1977, the Shippingport Atomic Power Station was operated as a light water breeder reactor using uranium and thorium. Over five years, the core produced more than 10 billion kilowatt-hours of thermal power. In 1982, the reactor was shut down to conduct a detailed fuel examination. A 1987 report on the experiment showed that the core contained approximately 1.3 percent more fissile material after producing heat for five years than it did before initial operation. Breeding had occurred in a light water reactor system using most of the same equipment used in conventional reactors.
Data are from many sources, including the WNA, Atomic Energy Insights (AEI), ORNL, and from the history of the Los Alamos laboratory.	

2. NUCLEAR REACTIONS

There are three significant nuclear transformation or decay processes, all of which emit energy, and two of which that emit neutrons:

- Radioactive decay and alpha decay processes,
- Spontaneous fission (emitting neutrons) and,
- Induced fission (emitting neutrons).

2.1 Radioactive decay

This occurs in all radioactive isotopes. Transformation of a neutron or proton in the nucleus of a radio-isotope can kick out a negative beta particle or a positive beta particle respectively and transmute the element into a different one. Any residual energy instability after the beta emission is relieved by the emission of one or more gamma ray energies, or through other processes. For example, radioactive decay by beta emission occurs when tritium (H-3) emits a negative beta particle by decay of a neutron in its nucleus, to a proton, to become helium-3. In this rare case, no following gamma emission occurs.

Table 2. Radio-isotopic Power Data in Watts per Gram

Nuclide	Half-life (years)	Watts/g
H-3	12.32	0.325
Co-60	5.27	17.45
Kr-85	10.76	0.590
Sr-90	28.78	0.916
Ru-106	1.02	31.8
Cs-137	30.07	0.427
Ce-144	0.78	25.5
Pm-147	2.62	0.340
Tm-170	0.35	11.86
Po-210	0.38	141.3
Pu-238	87.7	0.558
Am-241	432.7	0.113
Cm-242	0.45	120.0
Cm-244	18.1	2.78

Data from Chart of the Nuclides.

Various compact nuclear energy systems are based upon the radioactive decay heat of certain radionuclides shown in Table 2. Some of these have long been used to produce thermo-electricity in many sensing and signalling applications where reliability is essential, but where it may be impossible or may not be reasonable to have a permanent human presence, such as at the Polar Regions or underwater, and in satellite energy systems. Some heart pacemakers formerly used Pu-238 as a reliable power source.

Alpha decay *is a radioactive decay process - emitting a doubly positively charged helium nucleus - that occurs in the heavy elements above thorium (Z=90) and in their radioactive daughters down to stable lead (Z=82).*

Relatively little energy is emitted by the radioactive decay process of a single atom (up to a few MeV), but in total, radioactive decay heating is responsible for the inner heat of the earth and all related geothermal activity from volcanism and earthquakes to continental drift. In an operating reactor at full power, about 7 percent of the total heat production is from the radioactive decay of the abundant, very short half-life, fission nuclides that occur in only trace quantities in nature. After shutdown, this decay heat drops to about 0.7 percent after 24 hours.

2.2 Spontaneous fission

This occurs only in the heavier elements starting with thorium (Z=90) and is shown for these heavier radio-nuclides in Table 3. It is a natural process similar to radioactive decay, and can be described with a branching ratio and a half-life usually much longer than that due to normal radioactive decay, but involves the naturally occurring fissioning of the nuclide. Both processes - radioactive decay, and spontaneous fission go on simultaneously as, for example, in natural uranium.

Table 3. Radioactive Half-life and Spontaneous Fission Half-life of Some of the Heavy Element Isotopes above Thorium (Z=90).

Isotope	Alpha Decay Half Life	Spontaneous Fission Branching Ratio (Percent)	Spontaneous Fission Half-life
Thorium-232 *	**1.405E10 a**	**<1E-9 percent**	**1.2E21 a**
Uranium-232	68.9 a	9E-10	6.8E15 a
Uranium-233 **	**159 200 a**	**6E-9**	**2.7E17 a**
Uranium-234	245 500 a	1.7E-9	1.5E16 a
Uranium-235 **	**7.03E8 a**	**7E-9**	**1.00E19 a**
Uranium-236	23 420 000 a	9.6E-8	2.5E16 a
Uranium-238 *	**4.468E9 a**	**5.4E-5**	**8.2E15 a**
Plutonium-236	2.858 a	1.4E-7	1.5E9 a
Plutonium-238	87.7 a	1.9E-7	4.75E10 a
Plutonium-239 **	**24 110 a**	**3E-10**	**8E15 a**
Plutonium-240	6 565 a	5.7E-6	1.14E11 a
Plutonium-241**	**14.35 a**	**2E-14**	**6E16 a**
Plutonium-242	373 300 a	5.5E-4	6.77E10 a
Plutonium-244	8E7 a	0.12	6.6E10 a
Americium-241	432.2 a	4E-10	1.2E14 a
Americium-242m	141 a	1.5E08	3E12 a
Americium-243	7370 a	3.7E09	2E14 a
Curium-240	27 days	3.9E-6	1.9E6 a
Curium-242	162.8 days	6.2E-6	7E6 a
Curium-243	29.1 a	5.3E-9	5.5E11 a
Curium-244	18.10 a	1.3E-4	1.32E7 a
Curium-245	8500 a	6.1E-7	1.4E12 a
Curium-246	4760 a	0.03	1.81E7 a
Curium-248	348 000 a	8.26	4.15E6 a
Curium-250	9700 a	80	1.13E4 a
Californium-246	35.7 h	0.00025	1.8E3 a
Californium-248	333.5 days	2.9E-3	3.2E4 a
Californium-249	351 a	5.2E-7	8E10 a
Californium-250	13.08 a	0.08	1.7E4 a
Californium-252	2.645 a	3.09	86 a
Californium-254	60.5 days	99.69	60.9 d
Fermium-252	25.39 hours	2.3E-3	125 a
Fermium-254	3.24 hours	0.06	228 d
Fermium-256	157.6 minutes	91.90	2.9 h
Nobelium-256	2.91 seconds	0.5	9 m
Rutherfordium-260	20.1 milli-seconds	98	20 ms

Data are from Chart of the Nuclides and other sources. * Fertile. ** Fissile.

Each fission event - whether spontaneous or induced - releases about 200 million electron volts (MeV) of energy as detailed in Table 4. This is a relatively small amount of energy, especially when compared with the greater energy released by natural radioactive decay in the same mass of a heavy nuclide. For example the total alpha decay energy from a mass of plutonium-238 (or uranium-235) is about a billion times greater than the spontaneous fission energy. However, when the fissioning rate is augmented to trillions of fissions each second, which occurs when fissioning is induced in uranium-235 in the reactor environment, a much larger total amount of energy is actually released.

Table 4. Approximate Distribution of Energy Released from the Fissioning of an Atom of U-235	
	MeV
Kinetic energy of lighter fission fragment	100
Kinetic energy of heavier fission fragment	67
Energy of fission neutrons	5
Energy of fission γ rays	6
β particle energy gradually released	7
γ ray energy gradually released	6
Neutrinos (energy escapes totally)	11
Total	202
It takes about 3.1E10 such fissions each second to produce 1 watt of power.	

All natural uranium undergoes a weak, spontaneous fission process in nature all of the time, occurring at the rate of about 7 fissions each second for every kilogram of natural uranium (all from uranium-238). These fissions produce micro-quantities of the same fission and activation nuclides that are found in much greater abundance in an operating nuclear reactor. Such spontaneous fission occurs all around us, as there are appreciable quantities of both uranium and thorium in most rocks and throughout most soil profiles in the world. We do not notice it as the process is so rare, and we cannot sense or measure any obvious effects, as the emitted neutrons travel barely more than a few micro-metres before being absorbed by surrounding, relatively inert materials. It is also one of several ways in which the chain reaction in a nuclear power plant - containing extremely pure non-fuel materials with which neutrons cannot significantly interact before they become thermalized and interact with fuel - may be initially started, albeit with difficulty; a process that could be likened to starting a jumbo jet with a hearing aid battery.

All three were common processes earlier in the history of the earth when radioactive minerals were more abundant than today. About 2 billion years ago, the natural abundance of uranium-235 was greater than about 3 percent of all uranium. This meant that a spontaneous-fission induced chain reaction was possible in a rich uranium ore-body where light water was intimately associated with the ore. About 1.8 billion years ago such a reaction occurred in a rich uranium deposit at the present site of Oklo in Gabon, in central West-Africa (Figure 1). At the present time, spontaneous fission in nature cannot lead to a chain reaction to produce a natural reactor as occurred at Oklo, as the uranium-235 content is not sufficiently abundant, and all liberated neutrons from spontaneous fission are soon absorbed without a neutron multiplication effect. Consequently, the third process - induced fission as a continuing chain reaction - occurs today only in man-made reactors or where a

critical mass of uranium-235 or plutonium-239 is assembled and brought together in a weapon, or becomes a critical mass by accident.

Such accidents are localized and rare, but usually occur during reprocessing, when critical concentrations may be accidentally induced. In October of 1999, there was a criticality accident in a fuel- fabrication facility in Japan as a result of improperly trained operators. Such an accident involves a sudden surge in radiation fields, that rapidly fall once the critical assembly is dispersed or diluted as usually happens in a fraction of a second as the reaction heats and the matrix disperses as steam. One individual was extremely exposed and subsequently died, followed by a second fatality. Two were highly exposed (the fatalities), and 45 were less exposed. With the exception of the two fatalities, all recovered. There have been about 60 such criticality accidents in the world to about 2002. Few have involved more than one person, few result in fatalities, and there is little if any significant release of radiation once the critical assembly no longer exists. The usual injuries are from steam burns and short-term radiation effects, with rare fatalities or longer-term minor injuries and burns.

2.3 Induced Fission

Modern nuclear reactors rely upon the continuous production of neutrons (between 2 to 7 are released at each fission), some of which cause initial fast fissioning of uranium-238 before they can be thermalized. The fission neutrons that are not absorbed by competing processes, or lost from the reactor, are slowed to thermal energies (thermal neutrons have a speed of about 2.2 km s^{-1} and an energy of about 0.025 to 0.05 electron volts). Below this energy they are most likely to be captured by the large thermal neutron capture cross section of uranium-235 (or alternatively, may be captured by certain other transuranium nuclides shown in Table 5), inducing the uranium-235 to fission and produce the major part of the power output. Other nuclides with a large neutron capture cross section, also shown in Table 5, become heavier isotopes, or are transmuted to a range of transuranium nuclides, some of which are fissioned in the reactor.

Table 5. Thermal Fission and Activation Cross Sections of Some Transuranium Nuclides				
Isotope	**Alpha Decay Half Life**	**Total Cross Section (Barns)**	**Thermal Fission Cross Section (Barns)**	**Activation Cross Section (Barns)**
Uranium-232	68.9 a	162.3	76.7	74.9
Uranium-233 **	**159 200 a**	**588.4**	**531.2**	**45.2**
Uranium-234	245 500 a	119.2	0.006	99.75
Uranium-235 **	**7.03E8 a**	**698.2**	**584.4**	**98.8**
Uranium-236	23 420 000 a	13.7	0.06	5.3
Uranium-238 *	**4.468E9 a**	**12.1**	**1E-5**	**2.7**
Plutonium-236 **	2.858 a	331.1	169.4	145.4
Plutonium-238	87.7 a	586.7	17.9	540.3
Plutonium-239 **	**24 110 a**	**1026**	**747.4**	**270.3**
Plutonium-240	6 565 a	291.1	0.06	289.4
Plutonium-241 **	**14.35 a**	**1385**	**1012**	**361.5**
Plutonium-242	373 300 a	27.1	0.003	18.8
Americium-241	432.2 a	614.6	3.0	600.1
Americium-242m **	141 a	7669	6409	1254
Americium-243	7370 a	86.1	0.1	78.5
Curium-242	162.8 days	32.6	5.1	15.9
Curium-243 **	29.1 a	757.5	617.4	130.2
Curium-244	18.10 a	27.2	1.0	15.1
Curium-245 **	8500 a	2359	2001	346.4
Curium-246	4760 a	12.5	0.1	1.3
Curium-248	348 000 a	9.5	0.4	2.6
Curium-250	9700 a	11.2	0.002	0.4
Californium-249 **	351 a	2177	1666	504.5
Californium-250	13.08 a	1951	4.1	1779
Californium-252	2.645 a	64.8	33.0	20.7
Californium-254	60.5 days	17.1	2.0	4.5
Data are from NEA RCOM - June 1982, Scientific Co-ordination Group; Chart of the Nuclides and other sources. * Fertile. ** Fissile.				

In a stable reactor at any power level, there is a fairly steady state between the number of neutrons absorbed by all processes, including those leading to fission, and those produced by fission. As the fuel interacts with neutrons, the quantities of transuranium nuclides increases by progressive neutron activation of uranium-238 and heavier nuclides, and many of these are also fissionable with slow neutrons. This tends to increase reactivity and increase the energy output. However, other processes are also working to reduce reactivity, notably the gradual buildup of fission poisons, as well as reactor control processes. The controlling reactor programs detect and balance these competing processes to maintain the reactor power output at a determined level.

2.3.1 Neutron Sources

- Cosmic radiation at the earth's surface (about 0.01 neutrons cm^{-2} s^{-1}).
- Spontaneous fissioning (~7 s^{-1} in 1kg of natural uranium).
- Artificial sources of neutrons (alpha emitters: Pb-210, Po-210, Ra-226, Th-228, Pu-239, Am-241, mixed with beryllium powder) used for initial reactor start-up if spontaneous fission is inadequate. Emitting 1E4 to 1E7 neutrons cm^{-2} s^{-1}.

- Cyclotron accelerated deuterons acting upon hydrogen, tritium or beryllium-9. Capable of emitting 1E8 to 1E10 neutrons cm^{-2} s^{-1}.
- Reactor thermal fissioning of U-235 (1E8 to 1E16 neutrons cm^{-2} s^{-1}), and fast fissioning of U-238.
- Thermal fissioning of Pu-239, Pu-241 or U-233 (from Th-232 in a 'breeder').
- Delayed neutron precursors (e.g., Br-87).
- Photo-neutrons created by the capture of a 2.2 MeV γ energy by Deuterium in heavy water reactors.

$$2.2\ MeV\gamma + {}_1H^2 \longrightarrow {}_1H^1 + n$$

The second and third processes may be used to start a reactor with a new fuel load. Photo-neutrons can be used to kick-start a reactor that has been shut down for a short period of time, when there are no prompt or delayed neutrons, but the gamma energy required to produce photo-neutrons is emitted by relatively short-lived nuclides, so does not occur for very long. Graphite-moderated, and light water moderated reactors (PWR, BWR) do not have heavy water in the core and thus do not have this source of neutrons, so may add beryllium in the core to provide this γ,n reaction.

2.3.2 Neutron Interactions and Losses

There are many ways in which neutrons may be lost without interacting with nuclear fuel. Neutron losses and interactions occur by:

- Escape from the reactor core without being 'reflected' back into it
- Activation of non-fuel reactor components within the core
- Fast fission of uranium-238 and other fuel components
- Absorption by fuel components and in-growing transuranium isotopes without causing fission
- Absorption by fuel, with fission and energy production
- Absorption in fission 'poisons' (e.g., Xenon-135, Samarium)
- Absorption in reactor control 'poisons' (H_2O, Gadolinium, Boron, Cobalt)
- Absorption in reactor shutdown chemical 'poisons' (Gadolinium, Boron, Cadmium)

Reactor operation requires that, at any chosen power level, the two competing processes of neutron production and neutron losses are exactly balanced. The deliberate creation of a slight imbalance is used to either gradually raise or gradually reduce power. The sudden injection of neutron absorbing poisons, as metal rods or chemicals in solution, can be used to instantaneously curtail reactor operation and quickly bring it to a stable, shut-down state.

3. NUCLEAR FUELS, REACTORS AND REACTOR DEVELOPMENT

3.1 Nuclear Fuels

There are four fissile nuclides (fissionable with slow neutrons) of practical importance in reactors, and two fertile nuclides which can be 'bred' to become fissionable by the capture of fast neutrons:

3.1.1 Fissile Nuclides

- Uranium-235
- Plutonium-239
- Plutonium-241 (and some higher transuranium elements as shown in Table 5)
- Uranium-233

Uranium-233, uranium-235 and plutonium (generally) are all classified as Special Nuclear Materials (SNMs) as they can be fissioned with slow or fast neutrons and can thus be used in nuclear weapons. They can also initiate and sustain a nuclear chain reaction with slow neutrons, and can therefore be used as fuel in nuclear reactors, opening up a fuel resource that is millions of times more abundant and accessible than any fossil fuel or other source of energy outside of nuclear fusion.

Uranium-233 is a better fissile fuel than uranium-235, as it produces more neutrons on average, when fissioned by thermal neutrons, than does uranium-235.

- All of these, and uranium-238 also fission to a small degree with fast neutrons. Fast fissioning of uranium-238 contributes up to about 2 percent of reactor power, but fast fissioning alone in U-238 is incapable of sustaining a reactor nuclear chain reaction.

3.1.2 Fertile Nuclides

- Uranium-238 (fertile), is converted to uranium-239 with neutron capture, then beta decays to neptunium-239 which then beta decays to fissile plutonium-239. Further neutron captures lead to higher numbered fissile or fertile transuranium isotopes by fast neutron capture. About 40 percent of the energy output in a reactor is eventually derived from the thermal neutron fissioning of plutonium-239, and neutron capture transformations to higher plutonium isotopes, such as plutonium-241, which may fission or be transmuted to become fissionable.
- Thorium-232 (fertile), is converted to fissile uranium-233 by thermal neutron capture. U-233 has the most desirable fission characteristics of all of the fission radionuclides.

Fertile nuclides are fissioned to a small degree only by fast neutrons. Their primary value is as convertible fuel.

Only one of the fissile nuclides - uranium-235 - occurs (significantly) in nature, where it makes up 0.72 percent of all uranium. The two fertile nuclides - uranium-238 and thorium-232 - are 142 times and about 400 times respectively more abundant in nature. All fission reactors which contain significant quantities of either uranium-238 or thorium-232, breed fuel by their production of plutonium isotopes, or uranium-233 respectively. However, their 'conversion ratio' (fissile fuel produced relative to fissile fuel consumed) is much less than 'one' and they are consistently net 'burners' of fuel rather than net 'breeders'. Also, where re-processing is not practiced, none of the 'bred' fuel is returned to the reactor cycle.

True breeder reactors (fast breeders) are designed to have a conversion ratio greater than 'one', where they not only produce significant power, but also become net producers of fuel for subsequent reactor cycles. Reprocessing and recycling, is an integral part of the breeder cycle.

Nuclear spent fuel reprocessing and fuel recycling, derives the full energy potential from unburned uranium-238 (convertible to plutonium), the remaining unfissioned uranium-235, and fissionable transuranium isotopes (plutonium) in spent fuel, and increases the energy availability by a factor of about 70, from a quantity of uranium fuel relative to 'once through' fueling without reprocessing.

Adoption of a fast breeder reactor, which can breed uranium-238 and thorium-232 into fissile fuels (plutonium-239 and uranium-233) while producing energy, immediately opens up immensely more nuclear fuel for energy production relative to the 'once through' fuel cycle, and thus adds significantly to the fuel resource life. It also allows the approximately 1.6 million tonnes (by 2002) of depleted uranium from the enrichment process, and worth trillions of dollars in electrical energy, to be brought back into the fuel cycle.

The adoption of a breeder cycle also opens up much lower grades of uranium and thorium deposits which can then be economically exploited, and further multiplies the available fuel resource.

Most reactors at the present time use uranium fuel that is enriched to about 3 percent uranium-235. Others, like the CANDU and some graphite-moderated reactors, use natural uranium, but can also adopt fuel cycles that can use slightly enriched uranium and other nuclear fuels.

The U.S. light-water reactors are mostly fueled at this time (2003) with natural or depleted uranium, blended with uranium-235 that has been recycled from retired uranium-235 warheads from the former U.S.S.R. Other fuel components can include mixed oxide (MOX) fuel containing retired plutonium-239 warheads as the dominant fissile component as well as thorium-232. The use of retired warheads as nuclear fuel is the only reasonable way of partially destroying this material in a single pass through the reactor, and of safeguarding that which remains, by incorporating it into highly radioactive spent fuel, to be managed securely until spent fuel reprocessing and re-use

becomes an economic and rational consideration to unlock the potential energy in the 97 percent of fuel that is unused.

3.2 Early Reactors

The history of the universe appears to have been a history of 'singularities' or black holes. Black holes give birth to new galaxies as the super-dense materials explode in supernovae, giving birth to all of the chemical elements, and are redistributed to begin accretion and the formation of suns and planets in a cycle that occupies many billions of years. All eventually becomes quiescent and condenses back into a black hole or 'singularity', to begin the process again. The myriad stars (suns) that populate the heavens and are visible to us at night are nothing less than giant nuclear fusion reactors - billions of them.

3.2.1 The Sun

Our own sun formed as a result of this earlier explosion of several billions of years ago. It is an extremely large - though small in comparison with other suns - nuclear fusion reactor. All life on earth today owes its existence to nuclear energy from our sun (unless we originated elsewhere). The sun's energy arises from the conversion of hydrogen to helium with the emission of energy. As the sun ages and the hydrogen is consumed, the energy progression will entail the conversion of helium to carbon, a process which eventually will lead to the 'death' of our sun, as fusion energy decreases as the heavier elements are produced.

All fossil fuels exist because of the sun's nuclear fusion energy. Solar energy incident upon earth provides the environment for nearly all life forms including earlier vegetation and organisms that now occur as coal, oil, and gas, and the related wind, solar, hydropower energy and human life. Geothermal energy arises from the heating of the earth's interior by the natural decay of uranium and thorium progeny throughout the core and mantle. The only significant energy source on earth which has nothing to do with the sun's fusion energy or radioactive decay is tidal energy, which is a combination of strong gravitational effects from the Moon and Sun and weak gravitational effects from massive astronomical bodies further afield.

3.2.2 The Oklo Reactor

Several billions of years ago, there were natural operating fission reactors on earth.

There is evidence of several of them in one location at a place called Oklo, shown approximately in Figure 1, in Gabon, in central West Africa.

At that time, in the early history of the earth, the relative proportion of uranium-235 to uranium-238 was sufficiently abundant to support a natural fission reactor where conditions were ideal. These required a sufficiently rich ore body, and a supply of water in intimate association with it.

Figure 1. Oklo Deposit and Natural Reactors

The possibility of a natural nuclear reactor in the distant past, had been raised by an American physicist, Paul Kuroda, in 1956. He determined the relative ratios of U-235 and U-238 for the early history of our planet, by calculating the reverse of the process of radioactive decay. Prior to about 2 billion years ago, the natural concentration of uranium-235 was above 3 percent as indicated in Table 6; sufficiently abundant to have supported a natural fission reactor. Such a reactor could have been started by neutrons from the spontaneous fission of natural uranium, provided the initially fast neutrons could be adequately moderated by light water in intimate association with a rich uranium ore-body. There were initially no obvious examples known to the science of the day.

Table 6. Isotopic Relative Abundance in Nature Before the Present Time

Time Before the Present	Weight percent U-235	Weight percent U-238	Weight percent U-234
Half-life (years)	**700 million years**	**4.468 billion years**	**In equilibrium with U-238**
Today	0.7202	99.2745	0.0055
500 million years ago	1.089	98.91	0.0055
1 billion years ago	1.645	98.35	0.0054
2 billion years ago	3.71	96.28	0.0053
2.5 billion years ago	5.53	94.47	0.0052
3 billion years ago	8.16	91.83	0.0051

The first such spontaneous nuclear fission chain reaction of this kind so far identified, existed on earth more than a billion years ago. It was not man-made nor the product of any intelligence. It was entirely natural, and it operated about 1.8 billion years ago, or about 1.8 billion years before humanity appeared on earth. There appear to have been about 6 or more (perhaps as many as 17) small reactor zones contained within several small uranium-rich ore-bodies just a metre or so wide, within a uranium ore zone that extended for several kilometres and was about half a kilometre across.

There are undoubtedly others on earth, but we haven't yet come across them in a way we can recognize.

While the several small reactor zones were critical, approximately 1.8 billion years ago, they released 15 000 megawatt-years of thermal energy by gradually fissioning the uranium-235, and transmuting uranium-238 to plutonium, so that about five to six tonnes of uranium were consumed. During this long reaction period about 5 tonnes of fission products as well as about 1 tonne of plutonium isotopes together with other transuranic elements were generated in the ore-body, just as they are within the fuel of an operating reactor today. As in such a reactor, the plutonium would additionally, and significantly contribute to the energy production. The 15 000 megawatt-years is equivalent to the thermal energy produced in a modern-day 1000 MW electrical production reactor operating at 100 percent capacity (33 percent efficient) for about 5 years.

In retrospect, the mechanism was very simple. Surface water percolated into the pure ore zone and initiated neutron multiplication of the spontaneous fission events that were taking place all of the time, causing the uranium-rich reaction zones to become supercritical for a short time. Fission heating rapidly increased, as each fission releases about 200 MeV of energy, until reactivity constraints - boiling away of the moderating water, and increasing fission poison production - limited any further energy increase and caused the reactor to first become just critical and then sub-critical. As heat could not be efficiently removed, the water would boil and be expelled towards the surface, thus closing down the reaction. As the fission products rapidly decayed - most of them within a few hours - the reactor would gradually, but slowly, cool over months or years, water would be drawn into it, and the fission process would eventually become critical, then supercritical and build up once more. The several reactor zones in the ore-body would be self-limiting by boiling off the moderator and by the buildup of fission poisons.

These reactors operated intermittently over about 500 000 years at a low power of no more than about 20 kW(th). Had anyone been present immediately above this site at that time, they would have been entirely unaware of what was going on beneath their feet. Neither neutron production nor radiation from any of these reaction zones would have been readily detectable at the surface.

A further interesting observation derived from the Oklo reactors, concerned their stability over the last 1.8 billion years. None of the fission or transmutation products were leached out of the ore zones, despite an intimate association with groundwater, and a near-surface location. This example of the remarkable stability of the fission products and the associated transuranium nuclides has been of great interest to scientists who are directly concerned with studying the stability of nuclear wastes emplaced in scientifically engineered and maintained structures, and who are charged with defining containment methods that will be stable for just a few thousand years.

3.2.3 The Chicago Pile (CP-1)

In December 1941, following Pearl Harbor, the U.S. committed itself to a project to develop and construct a nuclear weapon. This had followed from Roosevelt's 1938 decision to increase the research effort into nuclear physics; a decision assisted by the receipt of a letter from Albert Einstein, the foremost physicist of the day. It had been written in collaboration with Eugene Wigner and Leo Szilard concerning the

development of a nuclear weapon based upon fission, and the alarming possibility that Germany could be developing one. Indeed, Werner Heisenberg had been given this task in Germany.

In January 1942, Enrico Fermi's continuing work with graphite moderation and natural uranium was moved to a new secret project, code-named the Metallurgical Laboratory (Met. Lab.) at the University of Chicago. Fermi relocated to Chicago and in April began design of the Chicago Pile 1 (CP-1) which would become the world's first (man-made) nuclear reactor to achieve criticality. Initially, however, he constructed an experimental pile in one of the squash courts at Stagg Field at the university of Chicago. The pile had a projected reactivity (k) of 0.995, which meant that it could not have achieved criticality, though serving to provide confirmatory data of what a critical pile might achieve. Following that project, he planned the construction of CP-1, and was faced with the task of getting both enough pure graphite blocks, and sized natural uranium spheres of adequate purity and in sufficient quantity, to build a working demonstration reactor.

On December 1st of that same year, after 17 days of almost round-the-clock work in the squash court, putting together machined - boron free - pure graphite blocks, interspersed with uranium spheres - of which 22 000 were on hand - and neutron absorbing rods, Fermi believed that a critical configuration had been achieved. At that point, the carefully stacked 'pile' contained 36.6 tons (imperial tons) of pure uranium oxide, 5.6 tons of uranium metal and 350 tons of graphite blocks.

The next day, Fermi's crew carefully followed his instructions to withdraw the electrically operated control rods, the emergency rod, and lastly, the 'vernier' control rod by determined amounts, while others stood by with buckets of neutron absorbing cadmium salts, ready to apply an emergency shutdown by pouring their contents into the pile if such a response was required. Fermi observed the gradually increasing responses of the instruments inserted into the pile, as the control rod was adjusted, and calculated how close they were to the reactor becoming critical. The pile 'scrammed' automatically at one point as the threshold was set too low, so Fermi suggested they break for lunch. In the afternoon of December 2, 1942, CP-1 was brought to 'super-critical' (with a reactivity of 1.0006) and was allowed to reach a thermal output of 0.5 watts. A sustained nuclear fission reaction had been achieved in the South Side of Chicago. Ultimately, the pile was operated up to a maximum power level of 200 watts.

The first man-made fission reactor came briefly into existence, and the atomic age was born.

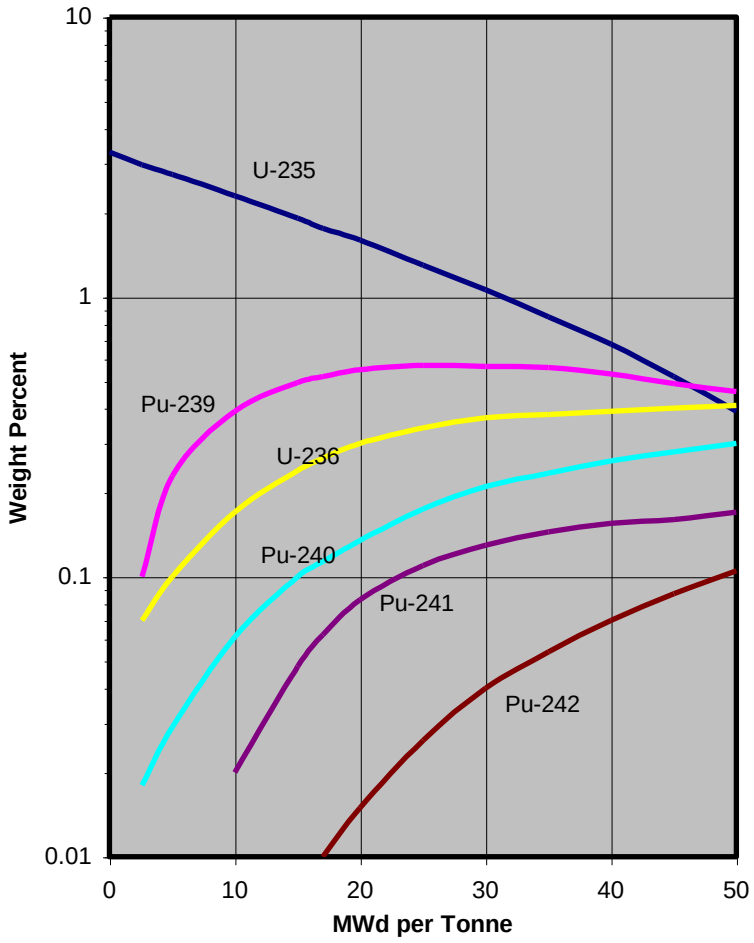
The CP-1 reactor was dismantled and moved to the Argonne Forest Preserve where it was reassembled as a much larger pile and renamed CP-2. This was followed in 1943 by CP-3, designed by Eugene Wigner, but moderated by heavy water.

3.2.4 Military, Naval, Research, Breeder, and Transitional Reactors

U.S. Military reactors to produce plutonium were being planned even before Fermi's first demonstration of CP-1, with the major facilities eventually being constructed on the Hanford Reserve in Washington State.

The production of plutonium for nuclear weapons requires that the reactor be operated for only a short period of time in order to produce (breed) as much plutonium-239 as possible with as little of the other transuranium nuclides as possible. Operation for longer than an optimum period before the fuel is changed (no more than a few weeks) leads to rapidly increasing production of less desirable plutonium and transuranium isotopes as shown in Figure 2. Many of these have significant spontaneous fission rates which would lead to instability and possible premature detonation in an impure isotope weapon. This is also the reason why plutonium production reactors are unsuited for reliable electrical power production and, conversely, why electrical production reactors are unsuited for nuclear weapons production.

Figure 2. Plutonium Isotope Ingrowth with Increasing Uranium-235 Burn-up in a PWR.



At the same time, methods of separating and enriching uranium-235 were developed. Uranium-235 not only had strategic weapons value, but could be used to fuel compact reactors which could be used as a controlled source of immense energy to propel surface ships as well as submarines. The main promoter of this major step forward in the use of reactors to produce energy was Admiral Hyman Rickover, who recognized that a compact Pressurized Water Reactor in naval vessels (and the fore-runner of today's hundreds of commercial PWRs), gave them a significant advantage over conventionally fueled vessels. They could make better use of the very large volume that had previously been used to store coal or oil fuel; they were fast; they could remain at sea for long periods, typically several years without need to return to their home port to refuel; and a nuclear submarine could remain submerged for weeks or months at a time without needing to surface to recharge batteries, and would thus be relatively undetectable.

Compact pressurized light water reactors using low enriched uranium fuel up to about 5 percent U-235, and light water moderator (equivalent to the ancient Oklo reactors, except for the pressure), were initially developed for use in submarines and aircraft carriers.

By increasing the degree of enrichment, the interval between refueling these reactors could be extended from about two years to five to ten years. Modern nuclear submarines are now designed with reactors that do not require to be refueled for the design life of the submarine.

The U.S. developed many small and experimental reactors, including modular small reactors for use in remote locations. These included a small reactor assembled and operated in Greenland at Camp Century from 1960 to 1965; a reactor operated in the Antarctic from 1962 to 1972 at McMurdo Sound; a reactor at Fort Greely, Alaska; one at Sundance Wyoming; and a 10 MW small PWR reactor that operated on a barge in the Panama Canal Zone and that was used from 1968 to 1975 to provide electricity to the Panama Canal Zone electrical grid. Others were developed for aircraft and rocket propulsion. More recently (2001), the U.S. DOE announced that it was studying the feasibility of using small modular reactors of less than 50 MW for remote communities or Islands. The main features were to be that they would require infrequent refueling, have intrinsic safety design features, be proliferation resistant and be essentially factory fabricated for easy assembly.

The rest of the world had not been idle while the US had taken these major historical strides forward. The U.S.S.R. and the British had also been developing their nuclear programs and commercial reactors from the 1940s. The world's first commercial nuclear power plant began operation in 1954 at Obninsk, sixty-five miles southwest of Moscow.

Research into the use of thorium as a nuclear fuel, which began in the earliest years of reactor development (Clementine in 1946 in the U.S.), was undertaken over many years in Germany, India, Japan, the Netherlands, the OECD, Russia, the U.K. and the U.S., but did not receive the same attention as uranium-plutonium reactors. Only India - which has a massive thorium resource - has an active program of reactor development based upon the use of thorium-232.

4. COMMERCIAL REACTOR TYPES

More than 30 countries operate about 443 commercial reactors (January 2003), producing about 17 percent of the world's electricity. By far the greater number are in the U.S. with more than 100 in operation, but closely followed by France and Japan. Some countries have modified the U.S. PWR design to their own use while others, with relatively modest nuclear programs, purchase the reactor design and contract out for fuel supply. Some countries have developed their own reactor technology based upon perceived advantages as well as the desire to be independent of U.S. political influence. The world's commercial reactors operating in early 2002 are as shown in Table 7 and Figure 3.

Table 7. Nuclear Power Plants in Commercial Operation (early 2002)

Reactor type	Countries	Number	GW(e)	Fuel	Coolant	Moderator
Pressurized Water Reactor (PWR, VVER)	US, France, Japan, Russia, & most others	259	231	Enriched UO_2, MOX	Water	Water
Boiling Water Reactor (BWR)	US, Japan, Sweden, Germany	91	79	Enriched UO_2	Water	Water
Gas-cooled Reactor (GCR & AGR)	UK	34	12	Natural U, enriched UO_2	CO_2	Graphite
Pressurized Heavy Water Reactor "CANDU" (PHWR)	Canada, South Korea, Argentina, India, Romania, China	34	16	Natural UO_2, PWR spent fuel, MOX	Heavy water	Heavy water
Light Water Graphite Reactor (RBMK)	Russia, Lithuania	17	13	Slightly enriched UO_2	Water	Graphite
Fast Breeder Reactor (FBR)	Japan, France, Russia	3	1	PuO_2, UO_2, DU (MOX)	Liquid metals	None
Other (HWLWR)	Japan	1	0.1	Slightly enriched UO_2	Water	Heavy water
	TOTAL	**439**	**352**			

Source: Nuclear Engineering International and others. Thorium-based breeder reactors have been researched since the 1940s, including a U.S. uranium-thorium HTGR (helium-cooled) experimental reactor at Fort St Vrain - now retired, and are still being researched in several countries, notably in India. The total number of reactors in operation by late 2002 was 442, with 35 more under construction. (IAEA).

Experience to the present time has shown that lifetime capacity factors (actual-operation relative to continuous-operation) have gradually increased in almost all of the world's operating PWRs to about 90 percent and more, an almost unthinkable possibility just a decade or so ago where 70 percent capacity factors in the U.S. were common. Increases in capacity factor, while reducing refueling and outage durations, coupled with design improvements in turbines, have seen electrical output increase across the U.S. reactors equivalent to adding almost another 25 nuclear power plants to the operational base, yet without any new construction taking place. This improvement has also ensured that nuclear power is consistently much cheaper than oil or gas fired electrical production facilities, at about half of their operating and maintenance costs, and is directly competitive with coal in most of its electrical generation uses (Figure 4).

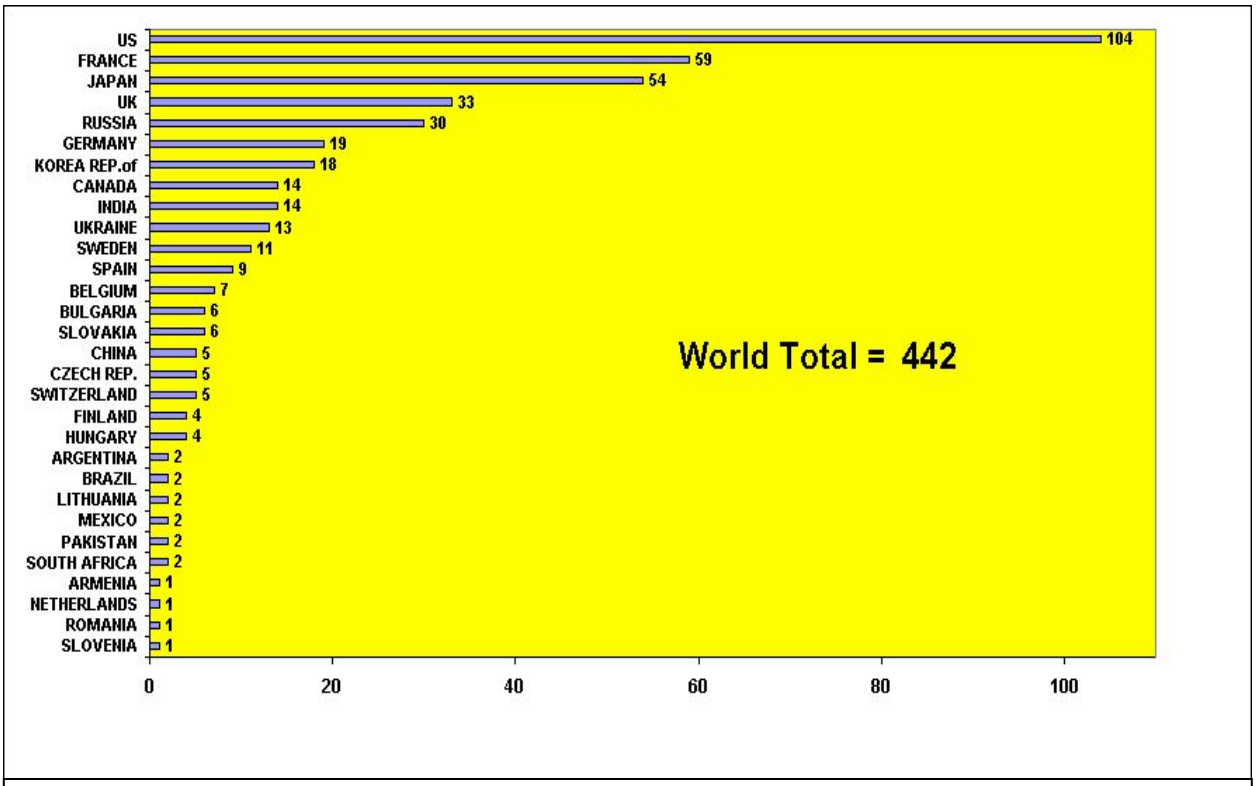
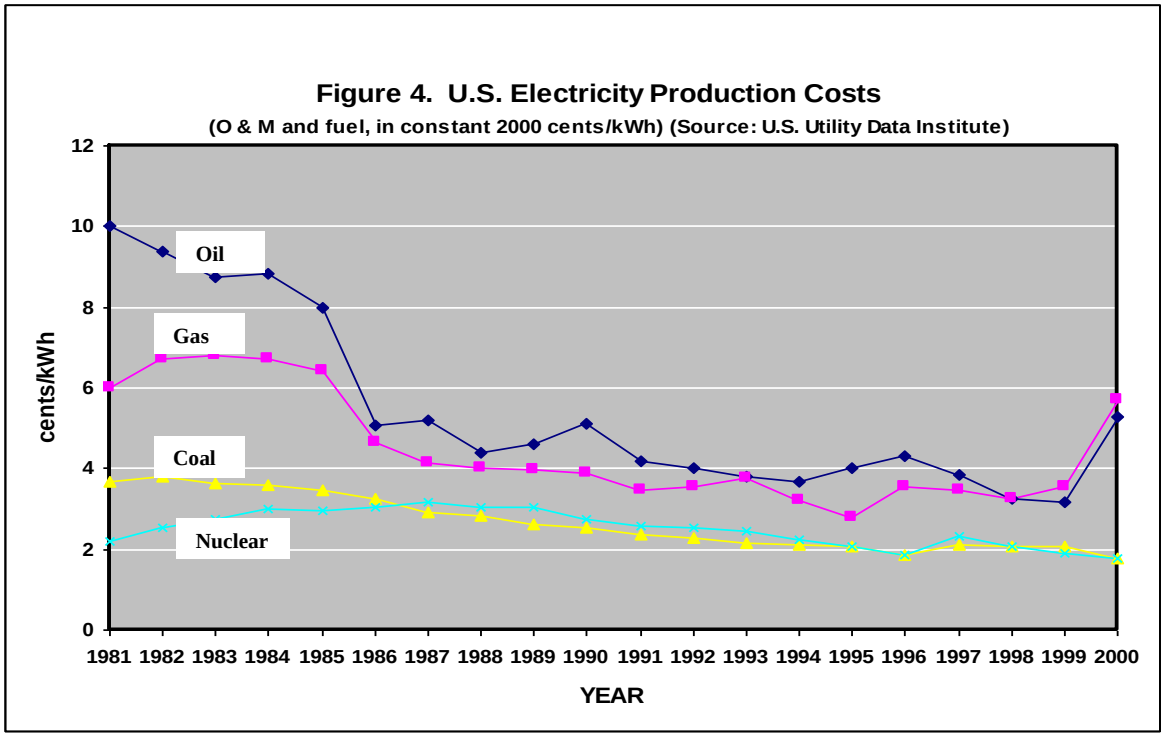


Figure 3. World Operating Power Reactor Listing (Partial) for Late 2002. Taiwan is not shown. (IAEA)



The approval of advanced modular-construction, and improved reactor designs, targeted at operating costs of about U.S.$1000 per installed megawatt, as opposed to about $1500 at this time, seems about to set the stage for a new generation of nuclear reactor construction, if concerns about the continued exploitation of fossil fuels and related pollution don't.

4.1 Main Operating Reactors

There are six main reactor types and variants of them in widespread use today:

1. The Pressurized Water Reactor (PWR).
2. The Boiling Water Reactor (BWR).
3. The Pressurized Heavy Water Reactor (PHWR).
4. The Gas-Cooled Reactor (GCR).
5. The Light Water Graphite Reactor (LWGR) and
6. The Breeder and Fast Breeder Reactors (FBR)

4.1.1 PWR

Most of the world's reactors are PWRs - Pressurized Water Reactors, similar to the one shown in Figure 5 - or variants of the design (VVER in Russia, and REP in France).

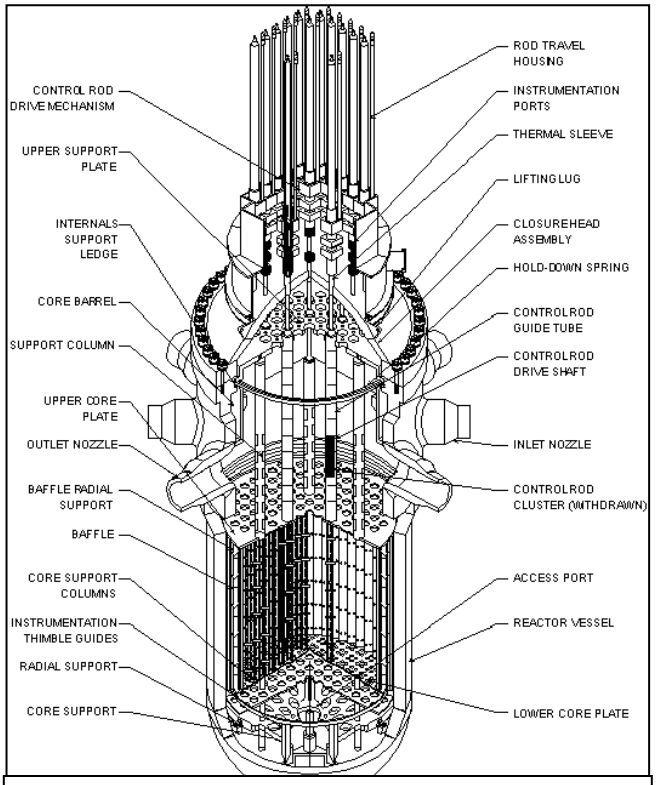


Figure 5. Schematic of the PWR Reactor. Source: US Nuclear Regulatory Commission.

The fuel is enriched to between 3 and 4 percent uranium-235 (some from retired uranium-235 warheads) and the moderator and coolant are light water at high pressure. Usually there are between two and four coolant loops. The primary high-pressure loop picks up heat from the fuel and transfers it through heat exchangers (steam generators or boilers) to a secondary lower-pressure loop, which passes the generated steam to a turbine for electricity production. The reactors are operated continuously for about 1 to 2 years before being shut down for re-fueling, when about one third (up to about 35 tonnes of the approximately100 tonnes) of core fuel is replaced. Such re-fueling outages used to extend for about 3 months or longer, but have now been reduced - in some reactors - to about 3 weeks.

4.1.2 BWR

The second most common kind of reactor is the Boiling Water Reactor (BWR), as shown schematically in Figure 6. The fuel is enriched to about 3 to 4 percent uranium-235 as for the PWR, but the physical size of the core is larger than for the PWR, and the pressure vessel is relatively low pressure. The moderator is light water, and the coolant is light water that is allowed to boil in the coolant circuit, with the steam passed directly to the turbine. Any radioactive activation products or contamination in the coolant circuit can be passed through to contaminate the turbine.

Together the PWRs and BWRs are known as Light Water Reactors. Advanced versions of all of the various reactors exist, incorporating all of the operating experience of the world, and with significant up-grading of materials, components and layout for ease of monitoring, repair and change-out, as well as with improved safety features and operating characteristics.

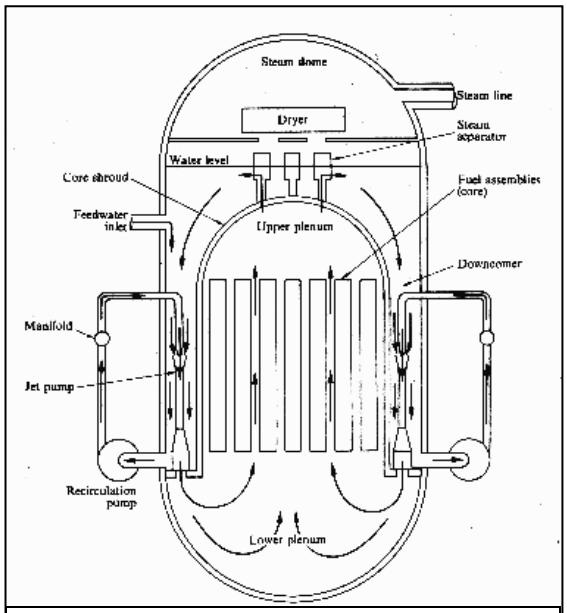


Figure 6. Schematic of the General Electric BWR Reactor.

4.1.3 PHWR

The current generation of Pressurized Heavy Water Reactors is manufactured and marketed by Atomic Energy of Canada Ltd., as the CANDU, a Canadian-developed reactor represented in Canada, S. Korea, Argentina, Romania, and China.

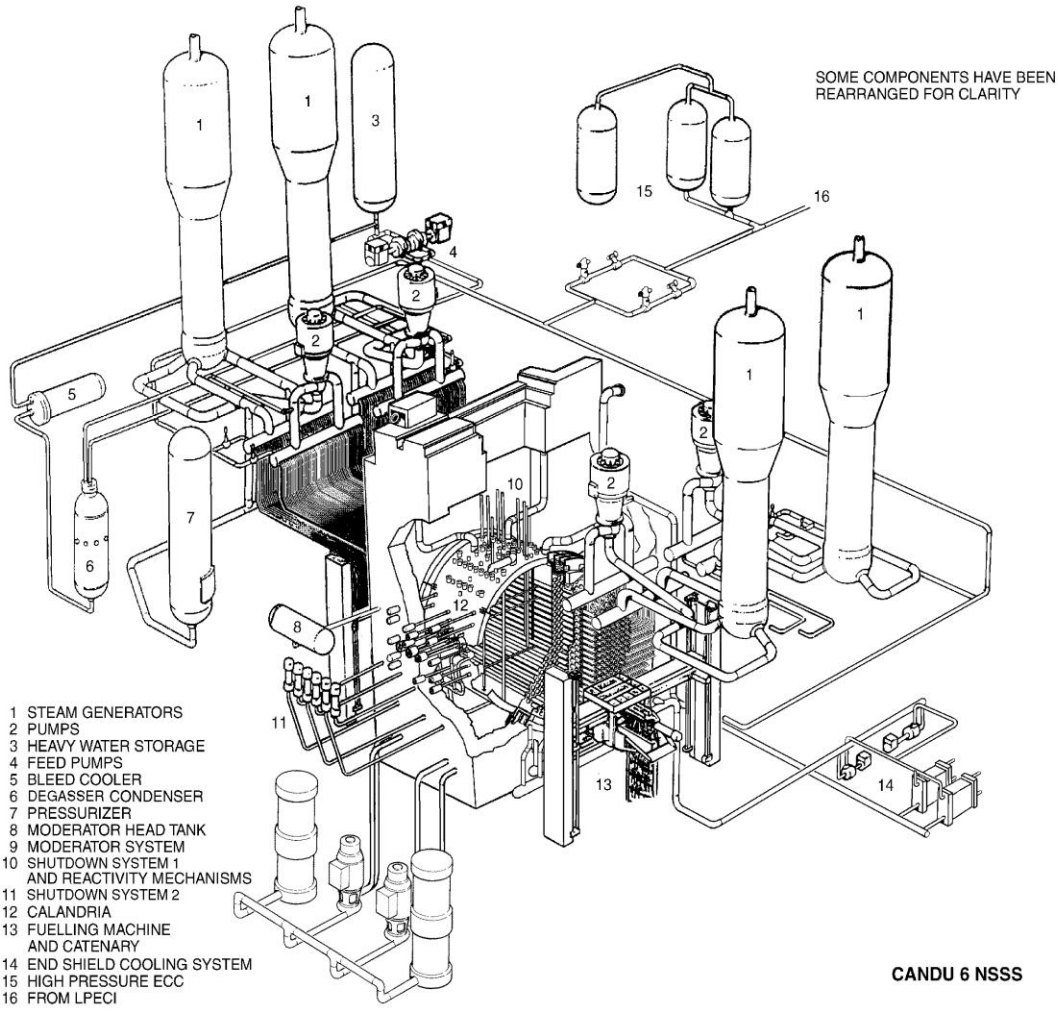


Figure 7. CANDU-6 Reactor Layout and Nuclear Steam Supply System (NSSS). Atomic Energy of Canada Ltd.

The basic CANDU reactor and support system layout is shown in Figure 7. It is typically fueled with 'once-through' natural uranium and is cooled and moderated by heavy water. Other fuel types and mixed fuels are possible including Low Enriched Uranium, plutonium in MOX fuel, depleted uranium and thorium (for breeding), as well as being capable of directly accepting the discharged fuel (after re-fabrication) from the 'once-through' Light Water Reactor cycle.

The CANDU PHWR can be operated as a breeder reactor with minor modifications.

The moderator heavy water is contained within a low pressure Calandria, through which pass about 380 horizontal pressure tubes, each containing about 12 fuel bundles. The CANDU is generally recognized for its overall neutron economy. Penetrations into the low-pressure Calandria permit the temporary insertion of materials directly into the neutron flux of the core, either for test purposes or for the production of medical isotopes including commercial quantities of cobalt-60 of which Canada is the world's major supplier.

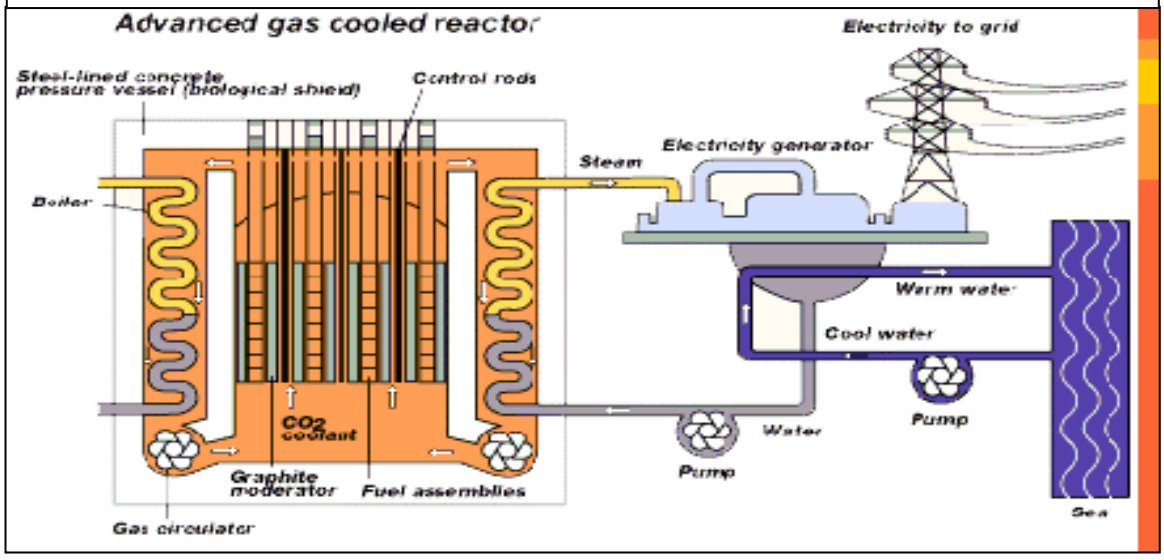
The primary heavy water coolant is maintained at 10 MPa and reaches 310 ^{o}C before starting to boil. The heat picked up by the primary coolant loop is transferred through boilers to pressurized light water which boils. The steam is transferred to a turbine to produce electricity. The PHWR (CANDU) reactor is refueled virtually continuously at power with about 15 fuel bundles (of about 4000 total) replaced for each full power day of operation. It is this refueling on-power that permits so much flexibility in the use and testing of different and blended fuels at any time and location in the core, as well as for any duration, and provides about a 5 percent operating advantage over those reactors which need to shut down to be refueled.

An advanced version of the CANDU (ACR) is based upon light water, rather than heavy water primary coolant, and using fuel that is enriched to about 2 percent uranium-235 to improve fuel burnup while reducing spent fuel disposal costs.

4.1.4 GCR

Various gas-cooled reactors are in operation in a few countries, mostly in the U.K. (Magnox) and France. They are fueled with natural or low enriched uranium, are graphite moderated, and usually cooled with carbon dioxide. A more advanced version in the U.K. is the Advanced Gas-Cooled Reactor (AGR), shown in Figure 8.

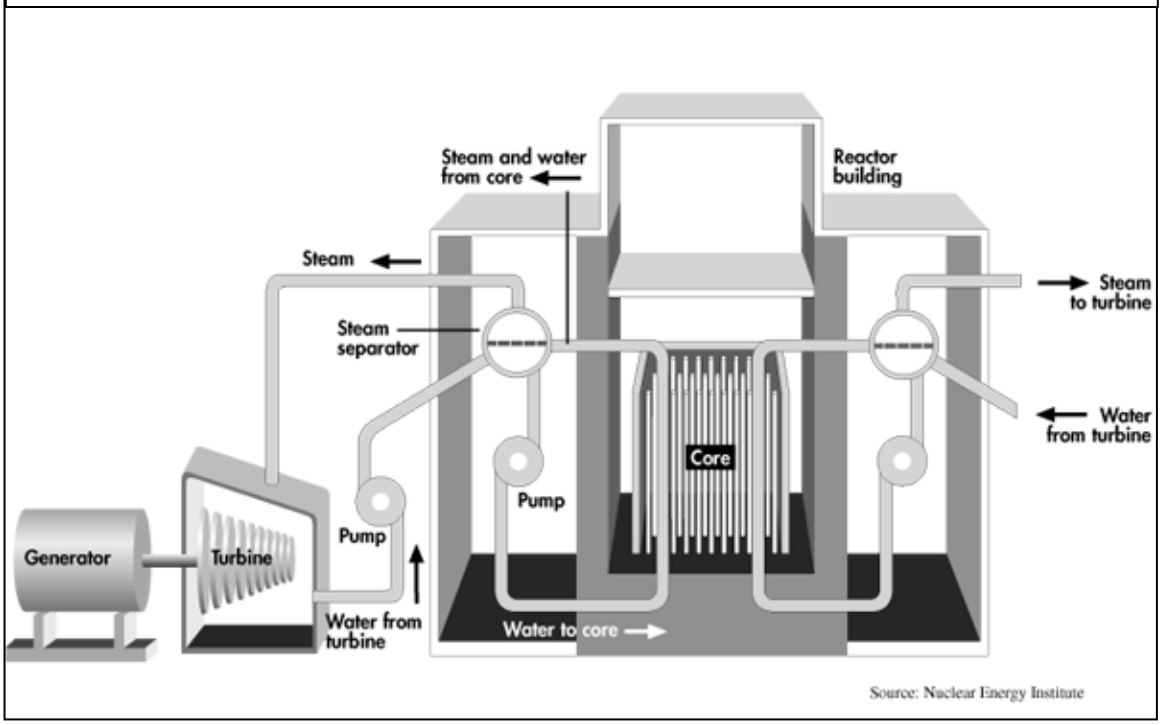
Figure 8. Advanced Gas-Cooled Reactor. Source: British Energy.



4.1.5 LWGR

The light-water, graphite-moderated reactors (RBMK), as shown in Figure 9, use slightly enriched uranium as fuel. They are Soviet designs that were built without containment structures. They are gradually being retired from use. The Chernobyl reactors are (were) of this type.

Figure 9. The Russian RBMK Graphite-Moderated Reactor without Containment. The Chernobyl Reactor was of this Type. Source: Nuclear Energy Institute.



4.1.6 Breeder Reactors

Most breeder reactors are still in the pilot and research stage. Most are shown in Table 8. There are Light-Water Breeder Reactors using uranium-thorium (Shippingport was operated as this before it was closed) and Liquid Metal Fast Breeder Reactors using plutonium and uranium. Neither have been developed to the degree that had been earlier anticipated, and are unlikely to proceed until the cost of uranium rises significantly.

Table 8. Fast Breeder Reactors in the World (2002)

Country	Reactor	Fuel	Type*	MW (thermal)	Operational
USA	Clementine	Pu	EFR	0.025	1946-53
	EBR 1	U	EFR	1.4	1951-63
	EBR 2	U	EFR	62.5	1963-94
	Fermi 1	U	EFR	200	1963-72
	SEFOR	Pu U	EFR	20	1969-72
	FFTF	Pu U	EFR	400	1980-94
	CRBRP	Pu U	DPFR	975	Cancelled
	ALMR	U Pu	DPFR	840	2005
	ALMRc	U Pu	CSFR	840	To be determined
UK	Dounreay DFR	U	EFR	60	1959-77
	Dounreay PFR	Pu U	DPFR	650	1974-94
	CDFR	Pu U	CSFR to EFR	3800	
France	Rapsodie	Pu U	EFR	40	1966-82
	Phenix	Pu U	DPFR	563	1973-
	Superphenix 1	Pu U	CSFR	2990	1985-98
	Superphenix 2	Pu U	CSFR to EFR	3600	
Germany	KNK 2	Pu U	EFR	58	1972-91
	SNR-2	Pu U	CSFR to EFR	3420	
	SNR 300	Pu U	DPFR	762	Cancelled
India	FBTR	Pu U	EFR	40	1985-
	PFBR	Pu U	DPFR	1250	2010
Japan	Joyo	Pu U	EFR	100	1977-
	Monju	Pu U	DPFR	714	1995-96
	DFBR	Pu U	CSFR	1600	To be determined
Kazakhstan	BN 350 #	U	DPFR	750	1972-99
Russia	BR 2	Pu	EFR	0.1	1956-57
	BR 10	U	EFR	8	1958-
	BOR 60	Pu U	EFR	65	1968-
	BN 600	Pu U	DPFR	1470	1980-
	BN 800	Pu U	CSFR	2100	To be determined
	BN 1600	Pu U	CSFR	4200	To be determined
Italy	PEC	Pu U	EFR	120	Cancelled
Korea	KALIMER	U	DPFR	392	To be determined
China	CEFR	Pu U	EFR	65	To be determined
Europe	EFR	Pu U	CSFR	3600	To be determined

* EFR - Experimental Fast Reactor; DPFR - Demonstration or Prototype Fast Reactor; CSFR - Commercial Scale Fast Reactor.

150 MW(thermal) is used for desalination. *Source: IAEA Fast Reactor Data Base*.

The doubling time to produce replacement fuel in the light water breeder reactor using thorium is up to about 20 years, whereas the liquid-metal fast-breeder fuel production rate is much shorter and more economically attractive.

The fast breeder reactor - consisting of a 'driver', a source of neutrons, and a fertile blanket, or absorber of neutrons - can be operated either as a net burner of nuclear fuel (to consume retired nuclear weapons plutonium), or as a net producer of nuclear fuel in the blanket, and can be adjusted between these two regions through choice and placement of fuel and blanket components.

The progressive development of the fast breeder reactor and fuel reprocessing is the logical extension of the existing generation of reactors. It has the overwhelming advantage of being capable of producing more fuel, than it consumes. Although, at first sight this seems to be illogical, in the same way as is a perpetual motion machine, it is not. It does not produce something from nothing. The potential energy was always in uranium and thorium to begin with, and just needed a mechanism to unlock it. That mechanism is the breeding cycle. When all economically derivable uranium-238 and all thorium-232 have been bred to fuel (which would take millions of years), then breeding can no longer take place.

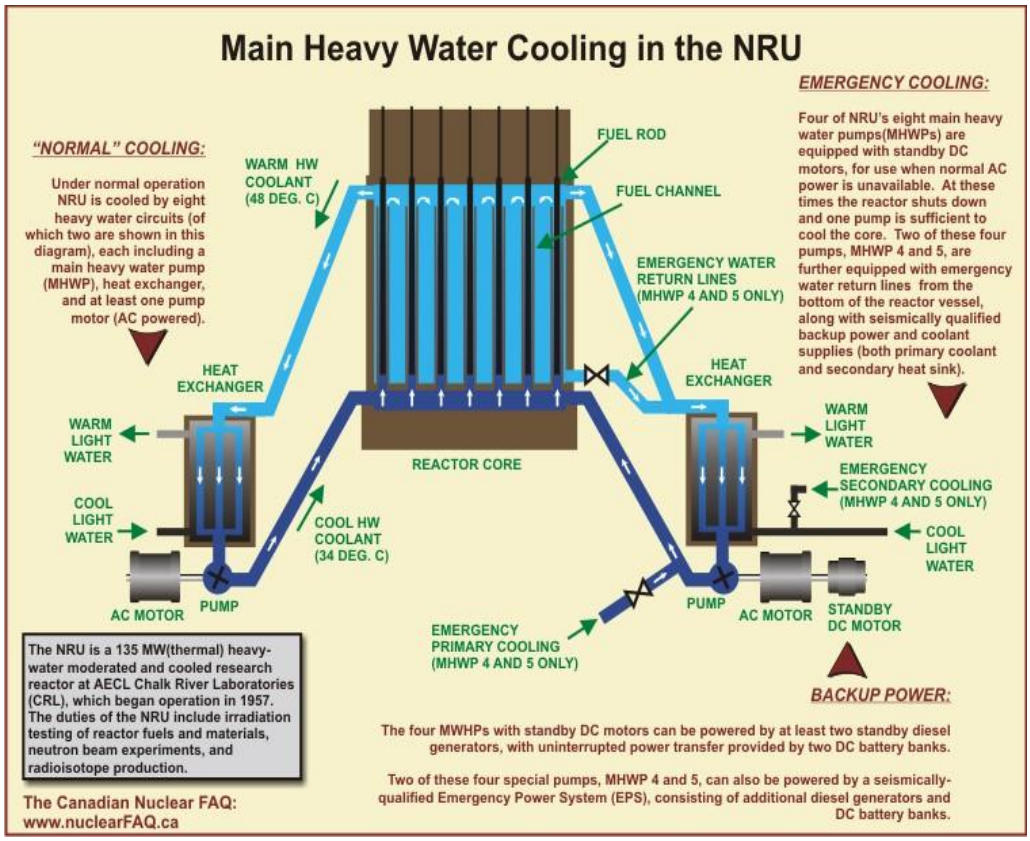
Fuel breeding - over and above that which takes place normally in every reactor, as uranium-238 is bred with fast neutron interactions to plutonium and other transuranium isotopes - could take place in many of the present-day moderated power reactors. It can occur if fertile fuel components (natural uranium, depleted uranium or thorium-232) are specifically introduced into the core with the usual reactor fuel. It occasionally is used on a minor scale, mostly for fuel research purposes and as a means of evaluating fuel behavior. With on-power refueling, the CANDU reactor is well suited to introducing a variety of fuel compositions into the core for this purpose. At the present time, uranium fuel is cheap and readily available, so commercial power reactors focus upon the most cost-effective power production method rather than upon operating in any other way that involves reprocessing, or the use of novel fuels.

In the U.S. the fast breeder reactor was one of the first reactors built and tested (Clementine), with several additional advanced pilot and test projects and small-scale reactors. The U.S. reactor program was, from its earliest days, based upon eventual transition to a commercial fast breeder reactor cycle to make the most efficient use of its nuclear resources. It developed extensive fuel reprocessing capability and designed its PWR and BWR program upon recycling and reprocessing their spent fuel. In 1977, then-president Carter banned reprocessing for political reasons concerning perceived proliferation in other countries. His decision had no obvious effect upon the way in which other countries approached nuclear power, but ironically, had a major effect upon the U.S. nuclear program and on the development of the fast reactor and breeding, while contributing nothing to overall security of energy supply (quite the reverse) nor to non-proliferation.

The great advantage of the fast breeder cycle is that it can breed its own fuel for succeeding fuel cycles from the fertile nuclides, uranium-238 or thorium-232. The choice of conversion ratio determines whether the reactor is a net burner of nuclides or a net producer of fuel. As a net burner of nuclides, the cycle is a consumer of fuels which can include retired plutonium nuclear weapons and transuranic wastes. Once these materials have been consumed and thus removed from possible weapons use, then the reactor conversion ratio can be adjusted to greater than one, to become a net producer of plutonium for use in succeeding fuel cycles.

The Conversion ratio (C) or Breeding ratio (B), is the rate of production of fissile atoms compared with the rate of consumption of fissile atoms. If the conversion ratio is small, the reactor is a net 'burner' of fuel. If the conversion ratio is between 0.7 and 1.0, then the reactor is a 'converter'. If the conversion ratio is greater than 1, then the reactor is a net 'breeder' of fuel.

Medical Reactors. (AECL, NRU).



4.2 Advanced and Future Reactors

4.2.1 Fast Breeder Reactor (FBR)

The general features of the fast breeder reactor were outlined above. However, the FBR is also the most logical progression in reactor development as a future reactor to replace the existing generations of fission reactor.

However, as long as natural uranium ore is cheap, it will be mostly used in 'once-through' fission reactors before there is any significant development of a breeder type of reactor for commercial purposes.

When the price of uranium rises significantly, then it will be cost effective to both reprocess spent fuel and engage in better utilization of the fuel resource, as achieved by the fast breeder cycle.

4.2.2 Accelerator-Driven System (ADS)

A conventional nuclear reactor relies upon the sustained production of neutrons from the controlled fission chain reaction of U-235 which is the fission 'driver'. These are gradually supplemented by neutrons from the fissioning of the increasing quantity of Pu-239 which slowly builds up within the reactor core from the neutron absorption within uranium-238. The neutrons to sustain this fission chain reaction are derived from the fission process itself within the reactor core.

An alternative source of neutrons which can maintain the fission chain reaction in the reactor, and thus becomes the 'driver', can be obtained from spallation of a heavy metal target (such as lead) located within the reactor, and bombarded by protons from an external high-energy accelerator, and using these neutrons to cause a specifically-designed marginally sub-critical assembly to become critical and super-critical as required.

The reactor control in this case is achieved by the neutron input from the heavy metal target associated with the proton accelerator. Control of the proton accelerator, can be used to either increase the reactor power, or to deprive the target of protons and thus cause the reactor to shut itself down as it is sub-critical without the accelerator operation.

The heavy metal spallation target within the reactor can be surrounded by various fuel components (a blanket) which would include fertile as well as fissile materials, and even transuranium isotopes and other long-lived nuclear wastes from conventional fission reactors.

The fertile components (e.g. thorium-232, or uranium-238) arranged around the spallation target could be bred to create fissile fuel for a continuation of the process. The loaded fissile fuel would provide sufficient neutrons to maintain the reactor in a sub-critical state. Any transuranium waste introduced into the core will either fission (mostly odd-numbered heavy nuclides), or undergo neutron capture leading to fission (mostly

even-numbered heavy nuclides). In this way, some of the more problematic long-lived transuranium nuclides and some fission nuclear wastes can be destroyed in a controlled manner or converted to shorter lived waste, while producing energy, rather than requiring long-term management.

The relative quantities of the various fuel assembly components, and the nature of the reactor operation can be chosen such that the reactor can be a significant power producer or a significant burner of nuclear wastes. After the initial startup, a significant fraction of the energy produced by the reactor - depending upon how it is fueled and operated - is required to maintain the operation of the accelerator.

Much of the early interest in ADS was because of their potential for destroying weapons-grade plutonium, as an alternative to combining it with uranium as mixed oxide fuel and burning it in conventional reactors, as is the case today. There are no accelerator driven systems in commercial operation, and with the likely continuing development of fast breeder reactors, albeit at a much slower pace than anticipated a few decades ago, and continuing to burn plutonium in conventional reactors, it is likely that they may never be brought into operation.

4.2.3 Fusion Reactor

After decades of research since the 1940s, the achievement of a sustained nuclear fusion reaction is making significant strides, but a commercial process is still probably at least fifty to a hundred years or more away.

One possible fuel, of many, for a fusion reaction is a mixture of deuterium and tritium. The atoms are 'fused' at plasma temperatures (about 100E6 degrees centigrade) in a magnetically confining toroidal chamber, but so far the reaction has not been sustained beyond a few minutes or so, though even this is a major advance from earlier reaction times.

The major project up to the present has been that known as JET (Joint European Torus) located in the U.K. During 1997, JET achieved new milestones including the production of 22 MJ of fusion energy in one pulse, achieving 16 MW of peak fusion energy and increasing to 65 percent; the amount of produced power relative to input power for a brief time. This international project has now been ended.

The next major international fusion project ITER (International Thermonuclear (Tokamak) Experimental Reactor) is being discussed, with a projected location either in Canada, France, Japan or Spain.

5. REACTOR CYCLES

There are two main reactor cycles at the present time, both based upon uranium-235 - the open or once-through cycle and the closed cycle in which spent fuel is reprocessed and the recovered uranium-235, uranium-238 and the transuranium nuclides are recycled back into the reactor. A third cycle - the fast breeder - based upon breeding fuel from uranium-238 and thorium-232 is developed, but is not likely to be more widely used until the price of uranium rises significantly.

5.1 The Closed Nuclear Cycle

The Closed Nuclear Cycle is schematically shown in Figure 10, for a typical PWR or BWR reactor where reprocessing of spent fuel is carried out.

The major stages are:

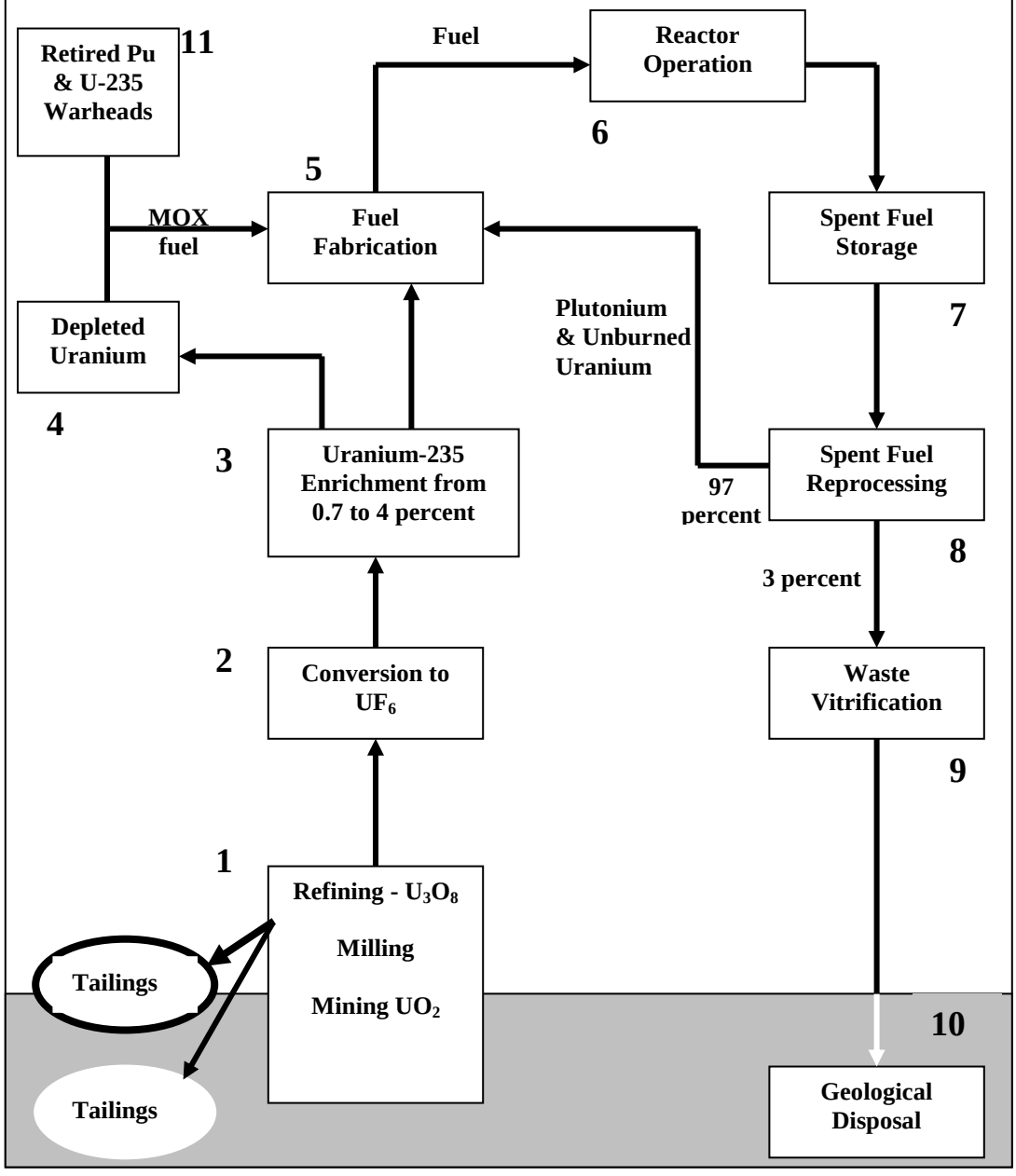
1. Mining of the ore, followed by milling and refining
2. Conversion of yellowcake to UF_6 to facilitate gaseous diffusion enrichment
3. Enrichment to about 3 percent uranium-235
4. Storage of depleted uranium (as UF_6) removed during enrichment
5. Fabrication of fuel as uranium oxide
6. Reactor operation for about 18 months, followed by partial defueling
7. Storing spent fuel for about 150 days
8. Reprocessing of spent fuel to remove fission wastes (3 percent) and return unused uranium-235, uranium-238 and transuranium nuclides (97 percent) back into the reactor cycle
9. Vitrification of the 3 percent fission wastes removed on reprocessing
10. Disposal of vitrified fission wastes in stable geological formations
11. Bringing retired plutonium-239 and uranium-235 warheads into the fuel cycle at the fuel fabrication stage (5) after blending with either natural uranium or depleted uranium to achieve the desired degree of enrichment.

The cycle is based upon not only the reprocessing of spent nuclear fuel, but also allows the inclusion of retired military weapons into the fuel cycle (stage 11), to be destroyed. Retired uranium-235 warheads (HEU) are diluted with natural or depleted uranium to achieve the desired degree of uranium-235 enrichment. Retired plutonium warheads are down-blended in the same way to form mixed oxide (MOX) fuel. The fissile component of fuel in this case is not uranium-235 but plutonium-239. This is the only cost-effective and rational method of removing military weapons from society and ensuring that they cannot be used in the future.

In the early years of U.S. nuclear reactor design and development, following Fermi's demonstration of the fission process in the CP-1 'Chicago Pile' in 1942, the nuclear cycle of the U.S. light water reactors was based upon a concept which included re-processing of the spent fuel from any reactor, and recovering the unused uranium and the produced plutonium, to be returned to the reactor cycle. This 'closed cycle' of operation was based

upon spent fuel being recycled into future fuel loadings with minor 2 to 3 percent make-up as required, to maintain operating reactivity.

Figure 10. The Closed Nuclear Fuel Cycle for a Typical PWR or BWR Reactor



5.2 The Open Nuclear Fuel Cycle

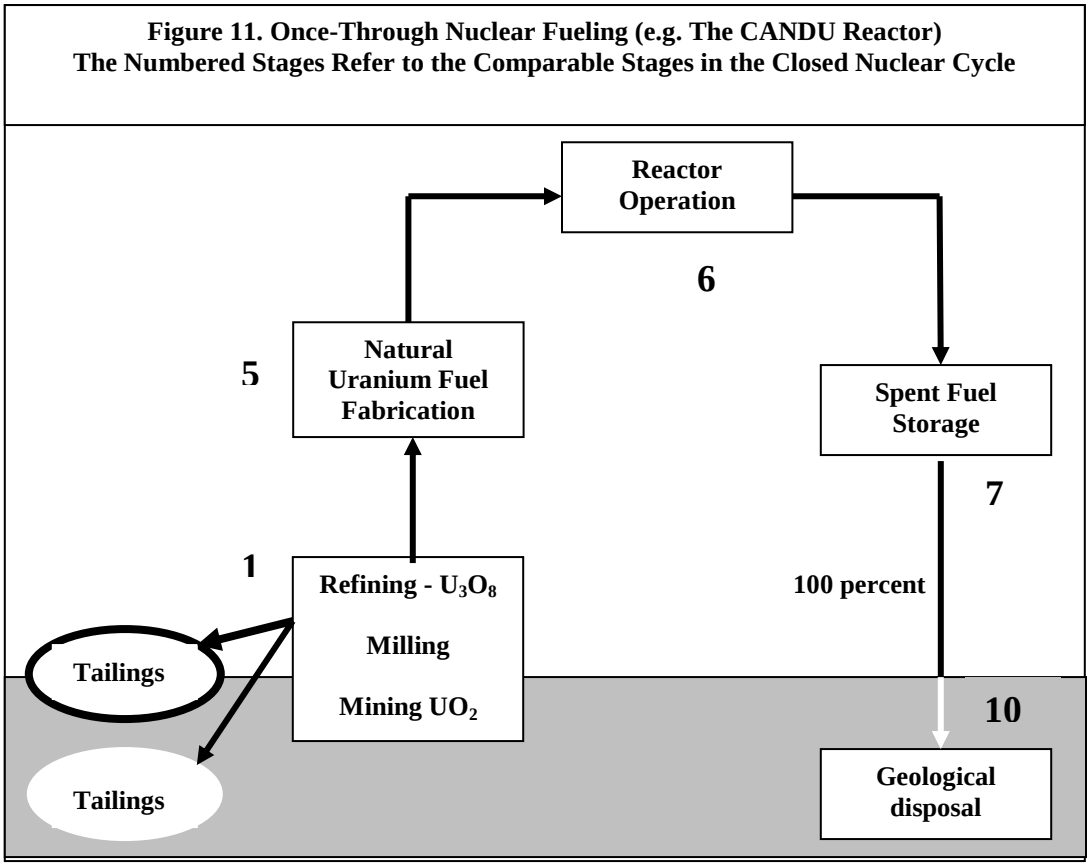
The open (once-through) cycle, shown in Figure 11, is used for those reactors where natural uranium is the fuel and there is no cost justification to reprocess.

Unfortunately, it has also been dictated by politics, as the operational process for reactors in the U.S. where - at least for the moment - enriched spent fuel is discharged from the reactor without consideration of reprocessing in the closed cycle as had been originally intended.

Where reprocessing is not considered for whatever reason, then the volumes of material that need to be managed and possibly disposed of as waste are about 30 times larger than the vitrified fission wastes that would otherwise be all that would need to be managed or considered for permanent disposal.

Natural fuel is relatively cheap, and the cost of reprocessing is sufficiently high that, at the present time, it is much cheaper to buy new fuel and manage the spent fuel than to consider reprocessing in the short term.

Figure 11. Once-Through Nuclear Fueling (e.g. The CANDU Reactor)
The Numbered Stages Refer to the Comparable Stages in the Closed Nuclear Cycle

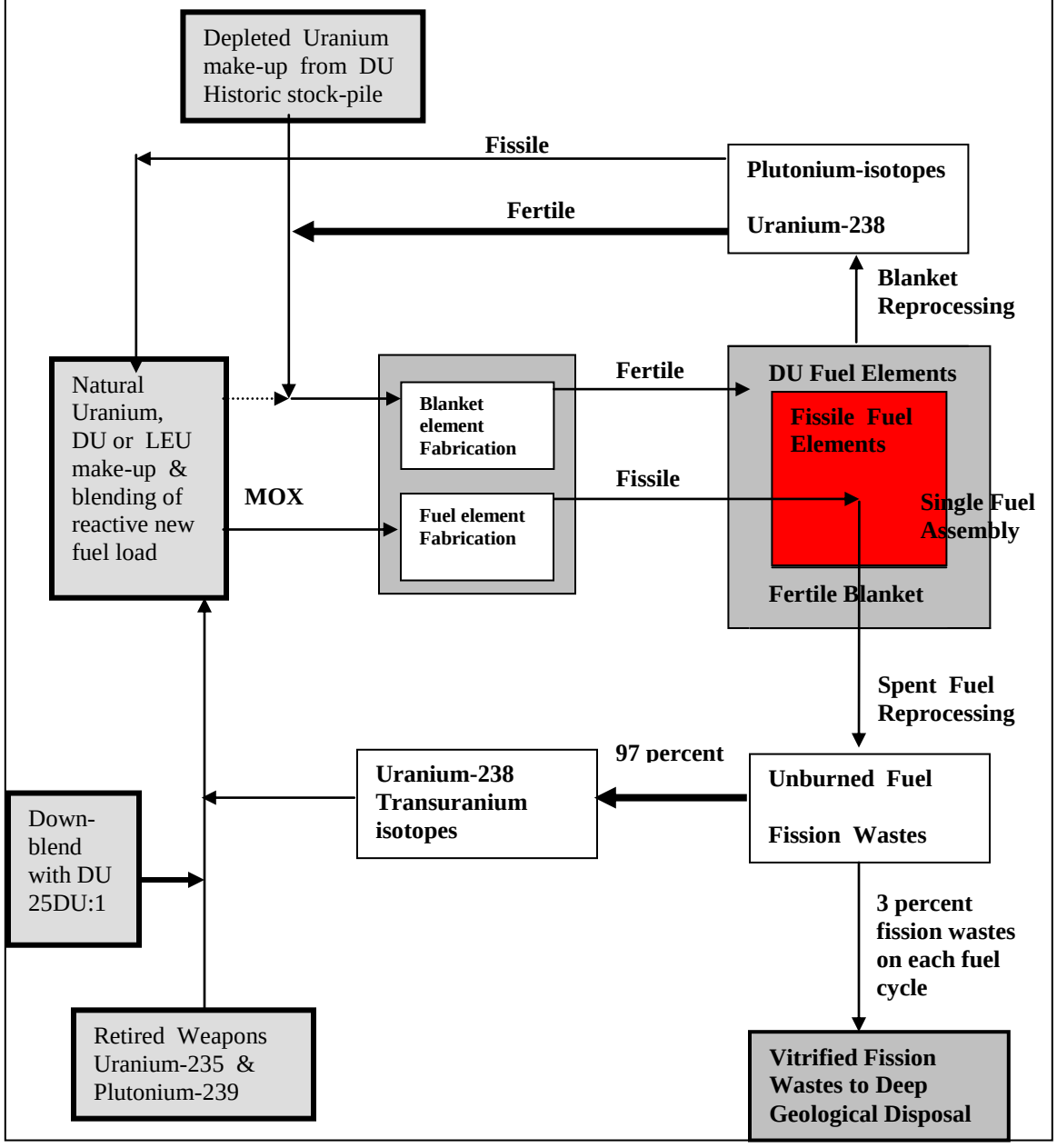


5.3 The Fast Breeder Reactor (FBR) and Fuel Recycling

There are several possible closed-cycle breeder reactor configurations and fuel options as well as operating characteristics.

A possible fast breeder cycle, based upon uranium fuel and continuous reprocessing, with inclusion of depleted uranium and retired nuclear warheads, is shown in Figure 12.

Figure 12. Fast Breeder Uranium Fuel Cycle, Schematic



The relative quantities of fissile materials in each of the reprocessing and fuel feed streams is directly influenced by the choice of conversion ratio for the operation of the reactor. Typical new fuel make-up in a large breeder reactor is about 2 to 3 tonnes per year.

The thorium breeder is slightly different in significant ways. The major fuel features of breeders are shown in Table 9.

Table 9. Fissile and Fertile Fuels in Breeder Reactors

Fissionable Source Of Neutrons ('Driver')	Fertile - Breeding - Material ('Blanket')	Fissionable Fuel Formed and Recycled
Uranium-235	Uranium-238 Thorium-232	Plutonium-239 Uranium-233
Plutonium-239*	Uranium-238	Plutonium-239
Uranium-233*	Thorium-232	Uranium-233

* Uranium-235 is the critical fissile nuclide at the inception of any reactor cycle. However, once a base supply of plutonium-239 or uranium-233 is formed then, with conversion ratios above 1, these bred, fissile fuels can continue the breeding process without uranium-235.

The entire nuclear program of the U.S., from its origin in the 1940s, was predicated upon the eventual development and use of the breeder reactor. The Fast Breeder Reactor (FBR) is the stage of reactor development beyond those of the 'Open Cycle' and 'Closed Cycle' reactors. It is capable of producing more fissionable nuclides than it consumes as was demonstrated by even the Shippingport PWR (Table 1, 1977).

In the breeder, some of the next-generation fissile materials are produced in the core and some are produced in a 'blanket' of fertile uranium-238 (initially from the massive stockpiles of depleted uranium) or thorium-232 that is placed around and at locations within the core to capture fast neutrons.

Re-processing of the spent fuel and the blanket provides the fuel for future reactor cycles. Addition of new blanket fertile material is all that is required to continue the cycle. With some re-arrangement - removing the blanket and making other fuel modifications - breeders can be turned into plutonium burners and become net consumers of plutonium, as a means of reducing plutonium weapons stockpiles.

Continuous reprocessing of both the spent fuel and the 'bred' fuel blanket, and incorporating the recovered unconverted uranium-238 and plutonium, (as well as transuranium nuclides from any source), into fast breeder fuel, thus eliminates the need to consider storing any significant quantity of transuranium wastes as they do not exist outside of the reactor cycle. This would vastly reduce the required isolation time for high-level waste to that of the significant fission nuclides, based upon the half-life of strontium-90 and cesium-137 (both about 30 years), to about 500 years at most, by which time they are no more radioactive than the naturally radioactive uranium in the starting fuel, as shown in Figure 13.

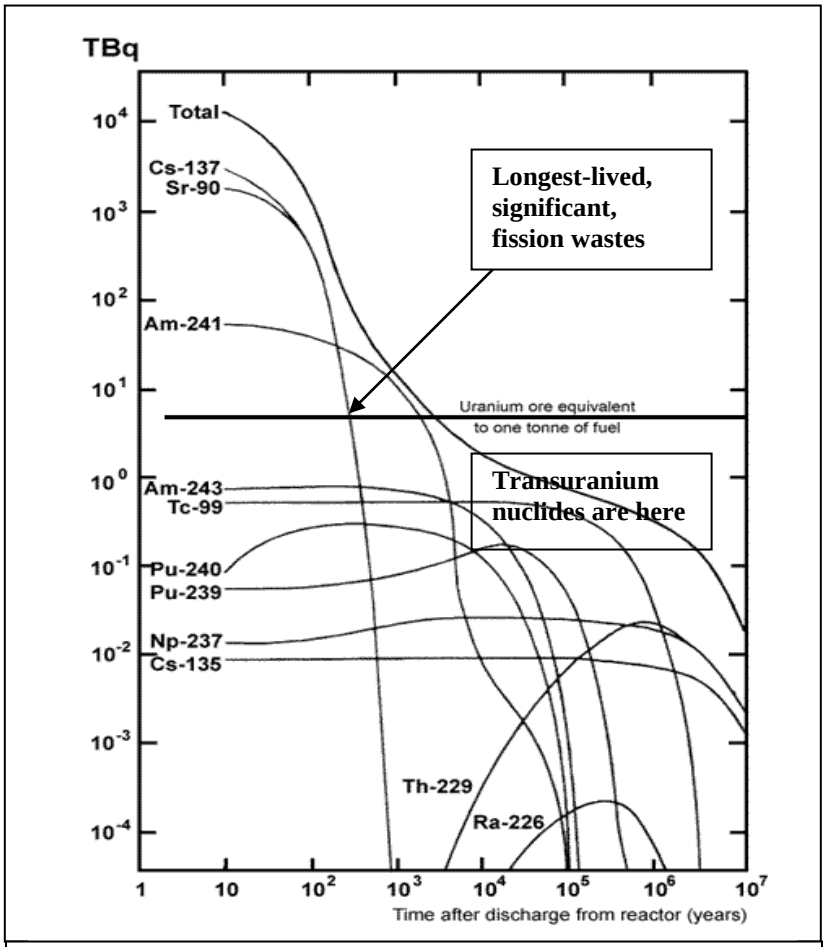


Figure 13. Activity of High-Level Waste from 1 Tonne of Spent Fuel
Source: IAEA, 1992 - Radioactive Waste Management.

The fast breeder reactor has been researched since the 1940s, with pilot projects built and operated in several countries. The breeder cycle using uranium, is based upon continuous reprocessing and recycling of the spent fuel and transuranium elements, as well as bringing back into the cycle, the depleted uranium that is currently stockpiled around the world and that is potentially worth hundreds of trillions of dollars as shown in Table 10, and is being added to each year.

The only true wastes from the breeder cycle are the small-volume, relatively short-lived, but highly radioactive fission nuclides produced in each reactor cycle. The breeder cycle based upon thorium-232, cannot produce significant plutonium radionuclides in the blanket, as thorium-232, unlike uranium-238 is at least seven steps away from producing plutonium rather than one or more, and breeds uranium-233 which is fissionable even more effectively than uranium-235.

Table 10. Estimated World Inventory and Value of Stored Depleted Uranium (2001), if Used in the Breeder Cycle.			
Country Or Enrichment Company	**2001 Inventory, (Tonnes)**	**Estimated Annual Increase (Tonnes)**	**Chemical Storage Composition**
US	590 000	20 000	UF_6
France	207 000	12 000	U_3O_8
Urenco (UK, Germany, Netherlands)	53 000	4000	UF_6
UK (BNFL)	30 000	0	UF_6
Russia	490 000	10 000	UF_6
Japan	5600	500	UF_6
South Africa	2200	0	UF_6
China	26 000	1000	?
Others	< 1000	?	?
Total	**1 404 800**	**47 500**	
US$ present energy value as electricity, assuming $30 MWh^{-1}.	**US$150 trillion**	**US$5 trillion**	
Most of the basic data have been revised from original DOE data.			

The breeder cycle:

1. Conserves energy by allowing better utilization and recycling of uranium-238, especially from the large stockpiles (1.6 million tons in 2003) of depleted uranium in the world.
2. Contributes to world safety through the reduction and elimination of weapons-plutonium stockpiles, if the world's reactors have not already done so.
3. Vastly reduces the need to continue mining uranium by about 90 percent or more, opens up much lower grades of deposit, and thus extends the reserves and resource life by thousands of years.
4. Recycles unburned and 'bred' fuel into the Fast Breeder, and reduces the 'radioactive waste' volume by a factor of about 30 in each cycle compared with the 'once-through' use.
5. Decreases the management time frame for wastes, as the longer-lived TU nuclides are destroyed in the reactor leaving only relatively short-lived fission nuclides.
6. Returns transuranium nuclides and uranium-238 from the reprocessed uranium fuel and uranium blanket into the reactor cycle, where they interact or fission with fast neutrons, contributing to the energy cycle while being destroyed in the core.
7. Continuously recycles and destroys plutonium-239 through the fuel cycle, where it is effectively controlled, while producing a large fraction of the energy (up to 40 percent of the energy output) in the reactor. At the same time, the highly radioactive spent

fuel matrix serves as a deterrent to any clandestine effort to sidetrack any of the plutonium.
8. Effectively increases the available uranium resource by about 100 fold, as uranium-238 (rather than the relatively rare uranium-235) then becomes the major uranium-fuel resource.
9. Reduces the need for expensive enrichment of uranium-235.
10. Is capable of using the even more abundant thorium-232 as a reactor fuel and thermally breeding it to uranium-233. Energy resources, which include thorium, are then significantly extended for many tens of thousands of years.

Obviously, in those countries with limited access to energy and uranium resources (France and Japan), the development of advanced reactor cycles including the Fast Breeder reactor is a very attractive long-term energy conservation proposition.

The implications of nuclear weapons proliferation require that countries, which seek to build and operate nuclear facilities, should be signatories of the Nuclear Non-Proliferation Treaty and should not seek to build or acquire weapons of mass destruction. They are also usually open to international inspection by the IAEA to ensure compliance. At the present time there are about 186 signatory countries and some notable rogue states which have weapons-development ambitions, though their efforts are gradually, decisively, and effectively being discouraged through the concerted actions of the United Nations.

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