NUCLEAR REACTOR OVERVIEW AND REACTOR CYCLES

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Contents

Summary

This chapter 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 Summary

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, or 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.

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. Maria 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 called "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 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.	

Table 1: Nuclear History Selected Milestones

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.

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.		

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

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 electricity in many sensing and signaling 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.

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Biographical Sketch

Dr. John K. Sutherland obtained a First Class Honors degree and PhD in Geology at Manchester University in England. He accepted a position in a research laboratory in Canada in which he was responsible for chemical and instrumental analyses of rocks, ores and minerals, including the development and use of X-ray diffraction, X-ray Fluorescence and Electron Microprobe analyses. In 1980, he joined the Health Physics Department of the local utility. He was responsible for the Environmental Radiation Monitoring Program, and for external beta-gamma dosimetry for the 600 nuclear facility employees over almost 20 years. He developed analytical techniques for the analysis of strontium-90, and for rapid analysis of vanadium in fly ash, and wrote the complete chemical analytical procedure for analyzing coal and fluidized bed combustion products in a coal burning facility. He was responsible for revising the Derived Emission Limits for the nuclear facility and for contributing to Shift Supervisor training and Radiation Protection training for plant employees, and contributed to Emergency Response Co-ordination and training. He conducted a radiation monitoring program of the nuclear waste and storage facilities over many years and was also engaged in monitoring spent fuel transfers to the storage facilities. During plant maintenance and other outages, he participated in Radiation Protection activities during maintenance work, including Fuel Channel replacement. He became an adjunct professor at the University of New Brunswick, where he taught Nuclear Safety and Reliability to graduate engineers. Since retiring, he has engaged in consulting work, including developing nuclear and radiation training for plant employees, emergency responders, and at other facilities where radioactive materials are used. He teaches and writes extensively on all radiation related issues.