NUCLEAR REACTOR CONFIGURATION

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Contents

Summary

Nuclear reactors require a particular and often unique arrangement of components in order to establish and maintain a self sustaining nuclear chain reaction. The arrangement

depends upon the nuclear properties of the materials. Fissile fuel is required in sufficient concentration to ensure a high enough probability that fission of the fuel will be caused by free neutrons. A moderator is required to reduce the energy and hence velocity of the neutrons so as to enhance the probability of their interaction with fissile fuel nuclei. Control rods or other devices are required to absorb excess neutrons so as to neatly balance the generation and absorption of neutrons to maintain a steady neutron density and hence power level. Finally a coolant is required to remove the heat generated by fission. The coolant in turn generates steam which is used in a steam cycle to drive a turbine and produce electric power.

Some reactor materials absorb neutrons more strongly than others so different fuel enrichments are used to compensate for this. Furthermore some reactor materials are more effective at slowing down or moderating neutrons than others so more space is required between the fuel elements where this moderation occurs. This leads to different sizes of reactor core when using different moderators. Generally coolants should not interfere with the moderation process and often the same fluid is used for both the coolant and moderator.

Generally there are only a few moderators and coolants suitable for nuclear reactors and the fuel is usually in a suitable form to be able to withstand high temperatures. Thus uranium dioxide is the most common fuel. It is usually clad in zirconium or stainless steel alloy so as not to absorb neutrons strongly. Possible moderators are light water, heavy water and graphite and coolants are usually light water, heavy water and carbon dioxide. Carbon, oxygen and hydrogen all have good moderating properties and low neutron absorption. Commercially operating nuclear reactors are thus limited to about half a dozen different types related to different combinations of moderator and coolant. Of these the light water moderated and light water cooled reactors are the dominant ones.

1. General Principles

1.1. Fission Energy

All atoms consist of a nucleus of protons and neutrons surrounded by a cloud of electrons. Generally for elements of low atomic mass numbers there are equal numbers of neutrons and protons in the nucleus since this arrangement represents the most stable configuration. As the atomic mass number increases however the weak repulsive forces of the similarly charged protons in the nucleus are compensated for by an increasing number of neutrons which contribute additional strong nuclear forces which bind adjacent protons and neutrons together. Thus at high atomic mass numbers there are approximately one and a half times as many neutrons as protons in the nucleus. Should an element of high atomic mass number split into two elements of lower atomic mass number, not as many neutrons will be required to create a stable configuration, and the surplus neutrons will be released.

The nucleons (neutrons and protons) in the nucleus are bound together by nuclear forces. When a nucleus is assembled, the binding energy attracting the individual nucleons is released. Conversely energy is required to separate individual nucleons from one another or from the nucleus. This binding energy is a maximum per nucleon for elements near the middle of the range of atomic mass numbers and is somewhat less for elements with high atomic mass numbers. This means that, if a heavy element fissions or splits into two midrange elements, the nucleons are bound together with a greater amount of binding energy per nucleon. The surplus energy is released as the nucleons come together more strongly. Because of the well known relationship between mass and energy, the release of binding energy is accompanied by a very slight decrease in the total mass of the constituents.

Elements with high atomic mass numbers are unstable and become more so as the atomic mass number increases. If a neutron is added to the nucleus of a very heavy element, the additional binding energy brought into the nucleus may excite it to the extent that it fissions. This occurs in two isotopes of uranium and two isotopes of plutonium. Of these four fissile materials only Uranium-235 is naturally occurring. Furthermore natural uranium contains only 0.7 percent of U-235. Nevertheless Uranium-235 is the primary fuel of all commercial power producing nuclear reactors.

When a U-235 nucleus fissions, the release of binding energy amounts to about 200 MeV or 32×10^{-12} J. Although a very small amount, this translates into a heat production rate of 950 MW if 1 kg of U-235 is totally consumed per day. In a typical nuclear power plant operating on a conventional steam cycle this could be converted into an electrical power output of 300 MW.

1.2. Nuclear Reactor Principles

Some heavy elements such as Uranium-235 can be induced to fission by adding a neutron to its nucleus. When fission occurs, the resultant lighter elements do not require as many neutrons in their nuclei to maintain a stable configuration and, on average, between two and three surplus neutrons are released. These neutrons are able to cause further fissioning of other U-235 nuclei and so establish a chain reaction. Such a reaction can be allowed to diverge as in an atomic bomb or controlled as in a nuclear reactor. For steady state conditions just one neutron on average from each fission should go on to produce another fission.

When fission occurs, the release of energy drives the lighter elements or fission products and the surplus neutrons away from one another at high velocity. Most of the energy is thus transformed into kinetic energy carried by the fission products. As heavy strongly charged particles, they do not travel any significant distance and dissipate their kinetic energy in the fuel by interaction with other atoms. The high energy fast neutrons, being uncharged, readily pass through the fuel and other reactor materials. There are varying probabilities that they will be absorbed by different nuclei. The probability of absorption by another U-235 nucleus to cause fission increases if the neutron velocity is reduced, so it is advantageous to reduce the neutron energies. This can be achieved by allowing the neutrons to make a series of non-absorbing collisions with light nuclei which, during an elastic collision, receive some of the energy from the neutron. The resulting low energy slow neutrons have a much greater probability of being absorbed in U-235 nuclei to cause further fissions. Some elements that have this ability of slowing down or moderating neutrons without significant absorption are hydrogen, deuterium, helium, beryllium and carbon. Hence light water (H_2O), heavy water (D_2O) and graphite (C) all make good moderators in nuclear reactors.

Most of the heat from fission is generated by the dissipation of the kinetic energy of the fission products. Since this occurs in the fuel near the point of fission, it follows that the fuel becomes the main source of heat in the reactor. In order to maintain a thermodynamic cycle to produce work, this heat must be removed continuously as it is produced. A suitable coolant is thus required to flow over the fuel elements and to remove the heat. The coolant must not readily absorb neutrons and must have suitable thermal properties. Coolants such as light water, heavy water, helium and carbon dioxide meet these requirements.

Finally, to ensure steady state operation, the number of neutrons allowed to go on to produce fission must be the same as the number in preceding generations of neutrons. To achieve the required balance, the reactor as a whole is designed to generate excess neutrons in each generation and to have a system of absorbing the excess so as to maintain and control the reactor at a steady load. This also allows for the number of neutrons in successive generations to be increased when increased power is required or to be decreased when power is to be reduced. Such control is usually achieved by having movable neutron absorbing control rods partially inserted into the reactor. By fully inserting the control rods the reactor may be shut down.

Thus a typical nuclear reactor consists of the following main components as shown in Figure 1:

- Fuel in which fission occurs and heat is generated
- Moderator to reduce the energy of the neutrons
- Coolant to remove the heat from the fuel elements
- Control Rods to maintain the proper neutron balance

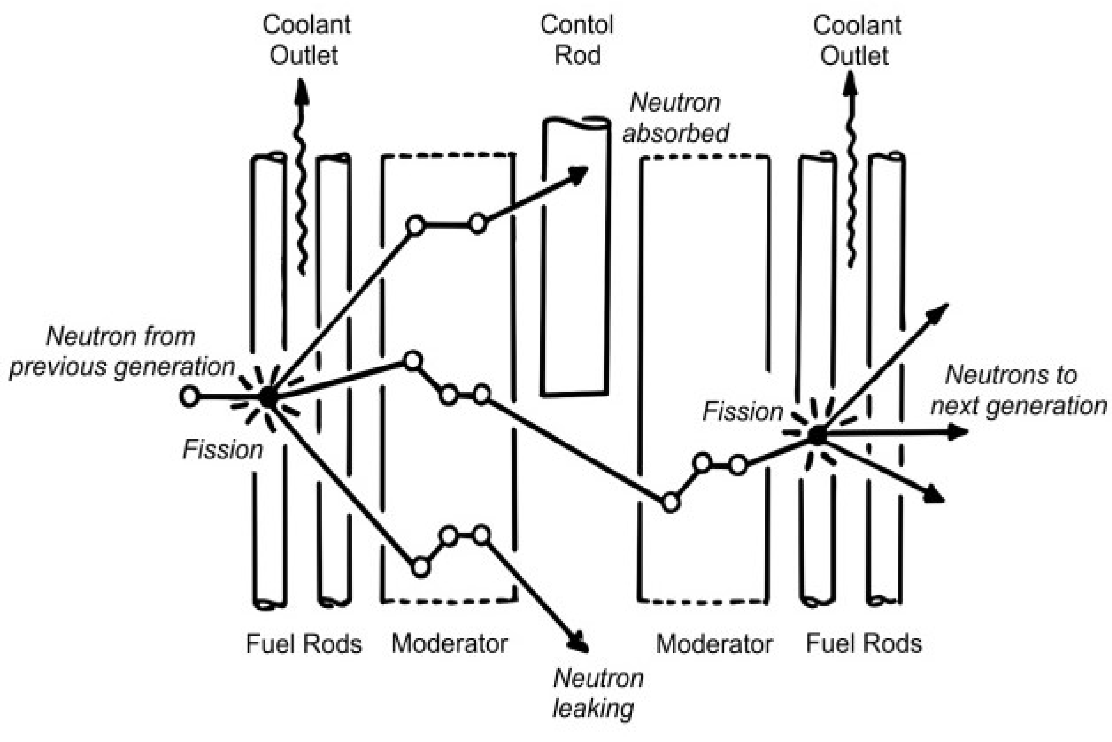

Figure 1: Nuclear reactor components

These components are usually arranged in a two dimensional matrix so that neutrons generated by fission in one fuel rod pass through the moderator before entering the next fuel rod. The spacing of the fuel rods depends upon the moderator properties and the distance required to reduce the energy of the neutrons. The fuel rods are made small enough to promote heat removal and are surrounded by the coolant. Often the coolant serves as a moderator as well. The control rods are made to penetrate between the fuel rods so as to effectively capture excess neutrons. Naturally some neutrons leak through the boundaries of the system and many are absorbed by the reactor materials or in the fuel without causing fission, so the control rods do not have to absorb a significantly large number of neutrons compared with the number causing fission. The actual configuration of the matrix and spacing of the fuel rods depends upon the fuel and moderator characteristics.

1.3. Fuel Burnup

As the fuel in the reactor is used up, the concentration of Uranium-235 decreases. This reduces the number of fissions occurring with a given number of neutrons. Furthermore some of the fission products produced absorb neutrons thus reducing the number of neutrons available to produce fission. These changes can be accommodated by withdrawing the control rods from the reactor and allowing more neutrons to be available in the fuel. After a long period of operation however such changes can no longer be accommodated and the fuel may have been depleted in U-235 to the point where a continuous chain reaction can no longer be sustained. At this point the reactor has to be refueled with fresh fuel.

With reactors that are partially refueled once a year the control rods do not provide an adequate range of control and a soluble neutron absorber is added in small quantities to the moderator. Its concentration is gradually reduced over time to compensate for the fuel burnup. Some reactors are designed for continuous on-load refueling. This is advantageous as the effects of fuel burnup and fission product production are negligible with regard to the overall conditions in the reactor.

2. Reactor Types

2.1. Reactor Development

Following the Second World War the development of nuclear reactors followed different paths in different countries depending upon the facilities developed during the war and the perceived military needs following the war. The first nuclear reactors served to generate Plutonium-239, another fissile material formed when Uranium-238, the major constituent of natural uranium, absorbs excess neutrons. Pu-239 could be easily separated from the original uranium fuel and was needed for atomic bombs. U-235 is also used in nuclear weapons but is difficult to separate from U-238.

The United States had isotope separation facilities for uranium so was able to pursue the development of reactors requiring the use of uranium fuel slightly enriched in U-235. The United Kingdom did not have such facilities so were forced to develop reactors using natural uranium.

When using natural uranium as a fuel, the low concentration of U-235 and the absorption of neutrons in U-238 necessitates the use of a moderator with an extremely low absorption cross section in order to establish a continuous chain reaction. Only heavy water (deuterium and oxygen) and graphite (carbon) have the required properties. This led Britain to develop graphite moderated natural uranium fueled reactors and Canada which had supplies of heavy water to develop heavy water moderated natural uranium fueled reactors. Heavy water however is very expensive to separate from ordinary water. If enriched uranium is available there is wider scope in the choice of a moderator as more neutron absorption can be tolerated. Thus light water (hydrogen and oxygen) can be used as a moderator. An advantage of light water as a moderator is that it is very effective in slowing down neutrons leading to a smaller moderator volume and a more compact reactor than with any other moderator.

Of the three moderators mentioned above, graphite is the least effective in reducing the neutron energy and requires the largest volume. Such reactors are the largest in size leading to high capital costs. Considering capital cost, moderator costs and enriched fuel supply all three of these became economically viable in their respective countries and commercial reactors for power plants subsequently evolved.

It is convenient to categorize nuclear reactors according to the moderator used even though there are variations within each category. Different coolants and different degrees of fuel enrichment have been employed to refine the designs such that there are currently some half a dozen distinct reactor types in commercial operation.

2.2. Commercial Reactors in Service

Table 1 shows the number, type and output of reactors operating in different countries. This table is representative of current commercial technology as most prototype and early commercial reactors have served their useful life and been decommissioned.

Country	**Reactor Type**	**Number in Service**	**Total Capacity (MW_e)**
Argentina	PHWR	2	935
Armenia	PWR	1	376
	PWR	7	5712
Brazil	PWR	1	626
Bulgaria	PWR	6	3538
Canada	PHWR	22	15439
China	PWR	3	2167

Taiwan	BWR	4	3104
	PWR	2	1780
Czech Republic	PWR	4	1648
Finland	PWR	2	890
	BWR	2	1420
France	LMFBR	1	233
	PWR	55	58515
Germany	PWR	14	1519
	BWR	6	636
Hungary	PWR	4	1731
India	BWR	2	300
	PHWR	8	1395
Japan	BWR	28	24682
	PWR	23	18425
	GCR	1	159
	HWLWR	1	148
Kazakhstan	LMFBR	1	70
Korea	PWR	10	8491
	PHWR	2	1279
Lithuania	LGR	2	2370
Mexico	BWR	2	1308
Netherlands	PWR	1	452
Pakistan	PHWR	1	125
Romania	PHWR	1	650
Russia	PWR	14	9114
	LGR	11	10175
	LMFBR	1	560
Slovakia	PWR	4	1632
Slovenia	PWR	1	632
South Africa	PWR	2	1842
Spain	PWR	7	5812
	BWR	2	1395
Sweden	BWR	9	7335
	PWR	3	2700
Switzerland	PWR	3	1692
	BWR	2	1385
Ukraine	PWR	13	11190
	LGR	2	1650
United Kingdom	GCR	20	3360
	AGR	14	8370
	PWR	1	1200
United States	PWR	69	65468
	BWR	36	32511

** Adapted from Nuclear News March 1998*

AGR: Advanced Gas Cooled Reactor
BWR: Boiling (Light) Water Reactor
GCR: Gas Cooled Reactor
HWLWR: Heavy Water Light Water Reactor
LGR: Light Water Graphite Reactor
LMFBR: Liquid Metal Fast Breeders Reactors
PWR: Pressurised (Light) Water Reactor
PHWR: Pressurised Heavy Water Reactor

Table 1: Nuclear Reactors in Service*

It is evident from Table 1 that certain types of reactors have been dominant in certain countries particularly in those developing their own reactors and that certain types of reactors have been favored by countries not having their own development program. Ignoring these preferences it is seen that, overall, the nuclear reactors listed from the top of Table 2 are the most widely used in the power industry.

The main reactor types listed in the table above will be described briefly in the following sections.

Reactor Type	**Number in Service**	**%**	**Total Capacity (MWe)**	**%**
PWR	250	58	221 552	64
BWR	93	22	79 803	23
PHWR	36	8	19 823	6
GCR	21	5	3 519	1
AGR	14	3	8 370	2
LGR	15	3	14 195	4
LMFBR	3	1	863	0
HWLWR	1	0	148	0
TOTAL	433	100	348 273	100

**Adapted from Nuclear News March 1998*

Table 2: Widely Selected Nuclear Reactors*

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Biographical Sketch

Robin Chaplin obtained a B.Sc. and M.Sc. in mechanical engineering from University of Cape Town in 1965 and 1968 respectively. Between these two periods of study he spent two years gaining experience in the operation and maintenance of coal fired power plants in South Africa. He subsequently spent a further year gaining experience on research and prototype nuclear reactors in South Africa and the United Kingdom and obtained M.Sc. in nuclear engineering from Imperial College of London University in 1971. On returning and taking up a position in the head office of Eskom he spent some twelve years initially in project management and then as head of steam turbine specialists. During this period he was involved with the construction of Ruacana Hydro Power Station in Namibia and Koeberg Nuclear Power Station in South Africa being responsible for the underground mechanical equipment and civil structures and for the mechanical balance-of-plant equipment at the respective plants. Continuing his interests in power plant modeling and simulation he obtained a Ph.D. in mechanical engineering from Queen's University in Canada in 1986 and was subsequently appointed as Chair in Power Plant Engineering at the University of New Brunswick. Here he teaches thermodynamics and fluid mechanics and specialized courses in nuclear and power plant engineering in the Department of Chemical Engineering. An important function is involvement in the plant operator and shift supervisor training programs at Point Lepreau Nuclear Generating Station. This includes the development of material and the teaching of courses in both nuclear and non-nuclear aspects of the program.