NUCLEAR POWER PLANTS

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Summary

The initial development of commercial nuclear reactors for the generation of electric power was constrained by the resources of the countries in which they were developed. In the United Kingdom the first reactors utilized natural uranium metal as the fuel and graphite as the moderator. In Canada, where heavy water was available as a moderator, natural uranium dioxide could be used as the fuel.

In the United States, which had enrichment facilities, enriched uranium dioxide was available as a fuel thus allowing light water to be used as the moderator. Over the years these basic types have evolved and as enriched uranium has become readily available there has been a trend towards the somewhat smaller and more compact light water moderated reactors which have the benefit of utilizing the same light water as the coolant.

Although there has been a slowdown in the construction of new nuclear reactors in the past few decades due to overcapacity in some utilities and public concern about the safety of nuclear reactors, statistics show a steady increase in the total capacity of nuclear power plants over each decade.

With the ever increasing demand for electric power and concerns about carbon dioxide emissions, nuclear energy has become the primary source of bulk base load electric power. France is the best example of the optimum use of nuclear energy in providing for the primary energy needs of the country.

Nuclear power plants have an excellent safety record due to rigorous licensing procedures for their design and operation. New concepts such as passive safety have resulted in advanced designs which are inherently safe under severe accident conditions.

Large plants have reached a plateau in thermodynamic efficiency, approaching the theoretical maximum, so there is little incentive to replace older units with newer ones. It is also less costly to refurbish an older unit than to build a new one. The result is that new plants under construction have been designed for a life expectancy twice that of older plants with refurbishment of key components part way through their lives being taken into account.

Nuclear waste is of concern, however, it is still a valuable resource.

Fuel re-processing allows the very long half-life transuranic products to be recovered for reuse and the shorter half-life fission products to be separated and disposed of in permanent storage facilities. This significantly reduces the amount of waste material and the time for it to decay to safe levels.

1. Introduction

1.1. General Structure

The general structure of the chapters within this topic is, as far as possible, consistent to facilitate cross referencing and comparison of different reactor types. The first seven articles generally have the following main section headings.

- Introduction
- General Configuration
- Core Arrangement
- Fuel Characteristics and Management
- Heat Transport
- Steam Cycle
- Operational and Safety Aspects

The eighth article has a slightly different structure but covers the same key aspects. This structure allows the reader to compare different reactor types more easily and, in particular, to note the differences.

Each article however has its own theme or style to avoid repetition and similar wording. Some articles describe or focus on one particular reactor of the group whereas others provide a generalized outline typical of most reactors of that type.

Some have detailed technical data while others are more descriptive. There is also obviously a difference in style and tense between reactors that have been decommissioned and those that have still to be built.

Some historical information has been given to show the evolution of different reactors. Some types such as the prototype SGHWR at Winfrith were very successful but were not taken to the commercial stage.

Other types such as the commercial HTGR at Fort St Vrain were plagued with difficulties and not taken to the next stage of development. Of the several different types of reactors that produced electric power only a few such as the PWR, BWR and CANDU are likely to continue in their current or advanced form while the PBMR is likely to evolve as a new commercial reactor type. Figure 1 shows the general categorization and evolution of the main reactor types.

Light Water Moderated Reactors		Heavy Water Moderated Reactors		Graphite Moderated Reactors		
				Water Cooled Reactors	Gas Cooled Reactors	
LWR				LGR	GCR	
Direct Cycle	Indirect Cycle	Direct Cycle	Indirect Cycle	Direct Cycle	Indirect Cycle	Direct Cycle
BWR ↓ ABWR ↓ ESBR	PWR ↓ APWR EPR	HWLWR SGHWR	PHWR CANDU ↓ ACR	RBMK	Magnox ↓ AGR ↓ HTR	GT-MHR PBMR

Figure 1 Main reactor categories and types

1.2. Demonstration and Prototype Reactors

The early development of most reactor types followed a series of steps to prove the particular concept. Typically the first step is to prove the physics of the configuration with a zero power reactor. Then, to prove the fuel and heat transport system, a demonstration unit of low power output is built. This may or may not produce electric power. A small turbine may be installed to utilize the available energy or the heat may simply be rejected in a cooling tower. The next step is to build a prototype plant of intermediate power output to gain operational experience without excessive capital expenditure. Some prototype units such as the SGHWR operated successfully for the normal life of a power producing unit. Others like the HTGR suffered many unforeseen problems and did not produce much useful power. They however have enabled new technical difficulties to be identified and resolved so that the final step to a full size commercial unit can be taken with confidence.

The initial development of the CANDU reactor is a good illustration of the progress from demonstration plants to commercial plants. The Nuclear Power Demonstration (NPD) plant producing 25 MW of electric power served to demonstrate the overall concept and was commissioned in 1962. This was followed in 1968 by the prototype Douglas Point of 218 MW gross electrical output. The first full scale CANDU plant then followed with four units each with a gross capacity of 542 MW. It was fully commissioned in 1973.

An example of a successful prototype reactor was the Winfrith Steam Generating Heavy Water Reactor (SGHWR) developed in the United Kingdom. Although the gross electrical output was only 100 MW it operated as a regular unit on the national grid system. It was commissioned in 1968 and ran for some 22 years. During this time it also served as a test reactor for proving various technical developments associated with this type of reactor. On the other hand the Fort St. Vrain High Temperature Gas cooled Reactor (HTGR) was plagued by numerous problems. Although a prototype with a gross electrical output of 341 MW it was intended to operate commercially. It took some 12 years however from the time of its first production of electrical power in 1976 for it to achieve its full generating potential. A little over a year later a new technical problem forced a permanent shutdown of the reactor. Many of the problems experienced were related to the developing technology and were resolved by appropriate design modifications.

Commercial reactors have also shown progressive development. The original Gas Cooled Reactor (GCR) of the Magnox type evolved to the Advanced Gas Cooled Reactor (AGR). The first commercial AGRs were very much like the last of the Magnox reactors while subsequent AGRs evolved to a slightly different design. Although the fuel was different, the construction and general configuration was similar.

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 was 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 necessitate 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. In this case 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, three different types of reactors 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	Net Capacity (MW_e)
Argentina	PHWR	2	935
Armenia	PWR	1	376
Belgium	PWR	7	5 801
Brazil	PWR	2	1 901
Bulgaria	PWR	2	1 906
Canada	PHWR	22	15 164
China	PWR	9	7 294
China	PHWR	2	1 400
Czech Republic	PWR	6	3 574
Finland	PWR	2	976
	BWR	2	1 720
France	PWR	58	63 130
	LMFBR	1	233
Germany	PWR	11	13 972
	BWR	6	6 457
Hungary	PWR	4	1 829
India	BWR	2	300
	PHWR	15	3 432
Japan	BWR	30	27 843
	PWR	23	18 425
Lithuania	LGR	1	1 185
Mexico	BWR	2	1 360
Netherlands	PWR	1	485
Pakistan	PWR	1	300
	PHWR	1	125
Romania	PHWR	2	1 412
Russia	PWR	15	10 964
	LGR	15	10 219

	LMFBR	1	560
Slovakia	PWR	4	1 705
	PWR	1	666
Slovenia	BWR	1	666
South Africa	PWR	2	1 800
South Korea	PWR	16	14 231
	PHWR	4	2 579
Spain	PWR	6	5 930
	BWR	2	1 509
Sweden	BWR	7	6 211
	PWR	3	2 705
Switzerland	PWR	3	1 700
	BWR	2	1 520
Taiwan	BWR	4	3 104
	PWR	2	1 780
Ukraine	PWR	15	13 095
United Kingdom	GCR	4	1 414
	AGR	14	8 380
	PWR	1	1 188
United States of America	PWR	69	67 986
	BWR	35	34 495

** Adapted from Nuclear News March 2009*
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 Breeder Reactor
PWR: Pressurized (Light) Water Reactor
PHWR: Pressurized 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.

Reactor Type	**Number in Service**	**%**	**Total Capacity (MWe)**	**%**
PWR	264	60	243 718	65
BWR	92	21	84 519	23
PHWR	48	11	25 047	7
LGR	16	4	11 404	3
AGR	14	3	8 380	2
GCR	4	1	1 414	0

LMFBR	2	0	793	0
TOTAL	**440**	**100**	**375 275**	**100**

**Adapted from Nuclear News March 2009*

Table 2. Widely Selected Nuclear Reactors

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Bibliography

Foster, A.R., and Wright, R.L. (1983), *Basic Nuclear Engineering*, Prentice-Hall, Englewood Cliffs, New Jersey, United States. [This text covers the key aspects of nuclear reactors and associated technologies. It gives a good fundamental and mathematical basis for the theory and includes equation derivations and worked examples].

Glasstone, S. (1979), *Sourcebook on Atomic Energy*, Krieger Publishing Company, Malabar, Florida, United States (original 1967), Van Nostrand Reinhold, New York, United States (reprint 1979). [This is a classic text (over 100 000 English copies sold and translated into seven other languages). It covers all aspects of atomic theory and nuclear physics from the initial development to the first commercial power reactors of several different types. It is an excellent historical reference].

Knief, R.A. (1992), *Nuclear Engineering: Theory and Technology of Commercial Nuclear Power*. Hemisphere Publishing Corporation, Taylor & Francis, Washington DC, United States. [This book gives a concise summary of nuclear and reactor physics before addressing the core material namely reactor systems, reactor safety and fuel cycles. It is a good reference for different types of reactors and historical developments].

Lamarsh, J.R. and Baratta, A.J. (2001), *Introduction to Nuclear Engineering*, Prentice-Hall, Upper Saddle River, New Jersey, United States. [This book provides a comprehensive coverage of all aspects of nuclear physics and nuclear reactors. It has a good descriptive text supported by all necessary mathematical relations and tabulated reference data.]

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 to South Africa 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 the 3 x 80 MW Ruacana Hydro Power Station in Namibia and the 2 x 900 MW 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. He has also been involved with the UNESCO sponsored Encyclopedia of Life Support Systems (EOLSS) as Honorary Theme Editor and primary author of the theme on Thermal Power Plants and has also assisted with the theme on Nuclear Energy and Reactors. Altogether he has contributed some three dozen chapters to this major source of international knowledge. As an adjunct professor at Waterloo University he has established and taught a graduate course in power plant thermodynamics to engineers in the nuclear industry as part of the UNENE masters program in Nuclear Engineering. He has served as Acting Chair and Chair in the Department of Chemical Engineering at University of New Brunswick and has been a consultant for Canadian Power Utility Services.