Reactor Physics and the Nuclear Fuel Cycle

Md Minhaj Ahmed

Abstract*—Questions regarding the feasibility of fusion power are examined, taking into account fuel cycles and breeding reactions, energy balance and reactor conditions, approaches to fusion, magnetic confinement, magneto hydro dynamic instabilities, micro instabilities, and the main technological problems which have to be solved. Basic processes and balances in fusion reactors are considered along with some aspects of the neutronics in fusion reactors, the physics of neutral beam heating, plasma heating by relativistic electrons, radiofrequency heating of fusion plasmas, adiabatic compression and ignition of fusion reactors, dynamics and control of fusion reactors, and aspects of thermal efficiency and waste heat. Attention is also given to fission-fusion hybrid systems, inertial-confinement fusion systems, the radiological aspects of fusion reactors, design considerations of fusion reactors, and a comparative study of the approaches to fusion power. The nuclear fuel cycle, also called nuclear fuel chain, is the progression of nuclear fuel through a series of differing stages. It consists of steps in the front end, which are the preparation of the fuel, steps in the service period in which the fuel is used during reactor operation, and steps in the back end, which are necessary to safely manage, contain, and either reprocess or dispose of spent nuclear fuel. If spent fuel is not reprocessed, the fuel cycle is referred to as an open fuel cycle (or a once-through fuel cycle); if the spent fuel is reprocessed, it is referred to as a closed fuel cycle..

Index Terms*— Nuclear Power Reactors, Reactor Technology, Technology Assessment, Thermonuclear Power Generation, Controlled Fusion, Feasibility Analysis, Nuclear Energy, Nuclear Fusion, Nuclear Physics, Plasma Heating, Plasma Physics, Radiation Damage, Relativistic Particles.

I. INTRODUCTION

Most nuclear electricity is generated using just two kinds of reactors which were developed in the 1950s and improved since. New designs are coming forward and some are in operation as the first generation reactors come to the end of their operating lives. Around 13% of the world's electricity is produced from nuclear energy, more than from all sources worldwide in 1960.

A. Nuclear Power Reactors

A nuclear reactor produces and controls the release of energy from splitting the atoms of certain elements. In a nuclear power reactor, the energy released is used as heat to make steam to generate electricity. (In a research reactor the main purpose is to utilize the actual neutrons produced in the core. In most naval reactors, steam drives a turbine directly for propulsion.) The principles for using nuclear power to produce electricity are the same for most types of reactor. The energy released from continuous fission of the atoms of the fuel is harnessed as heat in either a gas or water, and is used to produce steam. The steam is used to drive the turbines which produce electricity (as in most fossil fuel plants). The world's first nuclear reactors operated naturally in a uranium deposit about two billion years ago. These were in rich uranium ore bodies and moderated by percolating rainwater. Those at Oklo in West Africa, each less than 100 kW thermal, together consumed about six tonnes of that uranium. Today, reactors derived from designs originally developed for propelling submarines and large naval ships generate about 85% of the world's nuclear electricity. The main design is the pressurized water reactor (PWR) which has water at over 300°C under pressure in its primary cooling/heat transfer circuit, and generates steam in a secondary circuit. The less numerous boiling water reactor (BWR) makes steam in the primary circuit above the reactor core, at similar temperatures and pressure. Both types use water as both coolant and moderator, to slow neutrons. Since water normally boils at 100°C, they have robust steel pressure vessels or tubes to enable the higher operating temperature. (Another type uses heavy water, with deuterium atoms, as moderator. Hence the term 'light water' is used to differentiate.)

B. Components of a nuclear reactor

There are several components common to most types of reactors:

Fuel: Uranium is the basic fuel. Usually pellets of uranium oxide (UO2) are arranged in tubes to form fuel rods. The rods are arranged into fuel assemblies in the reactor core.

Moderator: Material in the core which slows down the neutrons released from fission so that they cause more fission. It is usually water, but may be heavy water or graphite.

Control rods: These are made with neutron-absorbing material such as cadmium, hafnium or boron, and are inserted or withdrawn from the core to control the rate of reaction, or to halt it. In some PWR reactors, special control rods are used to enable the core to sustain a low level of power efficiently. (Secondary control systems involve other neutron absorbers, usually boron in the coolant – its concentration can be adjusted over time as the fuel burns up.)

Coolant: A fluid circulating through the core so as to transfer the heat from it. In light water reactors the water moderator functions also as primary coolant. Except in BWRs, there is secondary coolant circuit where the water becomes steam.

Pressure vessel or pressure tubes: Usually a robust steel vessel containing the reactor core and moderator/coolant, but it may be a series of tubes holding the fuel and conveying the coolant through the surrounding moderator.

Steam generator: Part of the cooling system where the high-pressure primary coolant bringing heat from the reactor is used to make steam for the turbine, in a secondary circuit. Essentially a heat exchanger like a motor car radiator, Reactors may have up to four 'loops', each with a steam generator.

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Containment: The structure around the reactor and associated steam generators which is designed to protect it from outside intrusion and to protect those outside from the effects of radiation in case of any serious malfunction inside. It is typically a meter-thick concrete and steel structure.

C. Fuelling a nuclear power reactor

Most reactors need to be shut down for refueling, so that the pressure vessel can be opened up. In this case refueling is at intervals of 1-2 years, when a quarter to a third of the fuel assemblies is replaced with fresh ones. The CANDU and RBMK types have pressure tubes (rather than a pressure vessel enclosing the reactor core) and can be refueled under load by disconnecting individual pressure tubes.

If graphite or heavy water is used as moderator, it is possible to run a power reactor on natural instead of enriched uranium. Natural uranium has the same elemental composition as when it was mined (0.7% U-235, over 99.2% U-238), enriched uranium has had the proportion of the fissile isotope (U-235) increased by a process called enrichment, commonly to 3.5 - 5.0%. In this case the moderator can be ordinary water, and such reactors are collectively called light water reactors. Because the light water absorbs neutrons as well as slowing them, it is less efficient as a moderator than heavy water or graphite.

II. THE POWER RATING OF A NUCLEAR POWER REACTOR

Thermal MWt**,** which depends on the design of the actual nuclear reactor itself, and relates to the quantity and quality of the steam it produces.

Gross electrical MWe indicates the power produced by the attached steam turbine and generator, and also takes into account the ambient temperature for the condenser circuit (cooler means more electric power, warmer means less). Rated gross power assumes certain conditions with both.

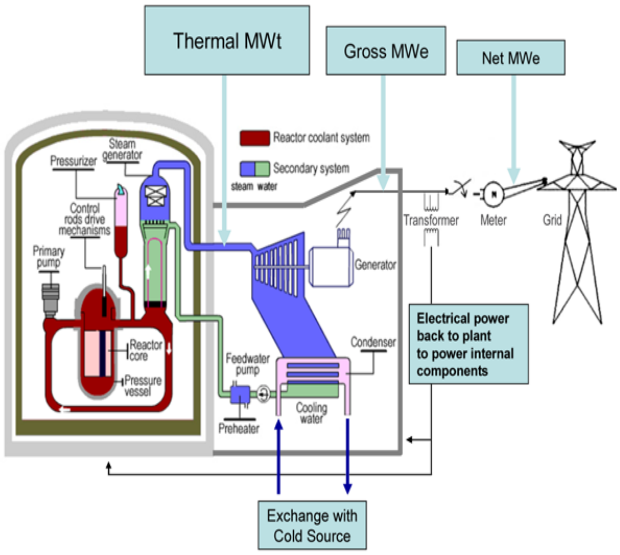
Net electrical MWe, which is the power available to be sent out from the plant to the grid, after deducting the electrical power needed to run the reactor (cooling and feed-water pumps, etc.) and the rest of the plant.
The relationship between these is expressed in two ways:

A. Thermal efficiency %,

The ratio of gross MWe to thermal MW. This relates to the difference in temperature between the steam from the reactor and the cooling water. It is often 33-37%.

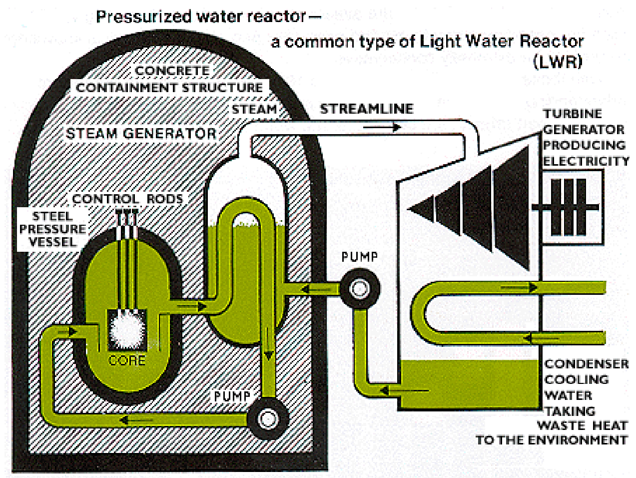
B. Net efficiency %,

The ratio of net MWe achieved to thermal MW. This is a little lower, and allows for plant usage.
In WNA papers and figures and WNN items, generally net MWe is used for operating plants, and gross MWe for those under construction or planned/proposed



III. PRESSURISED WATER REACTOR (PWR)

This is the most common type, with over 230 in use for power generation and several hundred more employed for naval propulsion. The design of PWRs originated as submarine power plant. PWRs use ordinary water as both coolant and moderator. The design is distinguished by having a primary cooling circuit which flows through the core of the reactor under very high pressure, and a secondary circuit in which steam is generated to drive the turbine. In Russia these are known as VVER types - water-moderated and -cooled.



A PWR has fuel assemblies of 200-300 rods each, arranged vertically in the core, and a large reactor would have about 150-250 fuel assemblies with 80-100 tonnes of uranium.

Water in the reactor core reaches about 325°C, hence it must be kept under about 150 times atmospheric pressure to prevent it boiling. Pressure is maintained by steam in a pressuriser. In the primary cooling circuit the water is also the moderator, and if any of it turned to steam the fission reaction would slow down. This negative feedback effect is one of the safety features of the type. The secondary shutdown system involves adding boron to the primary circuit.

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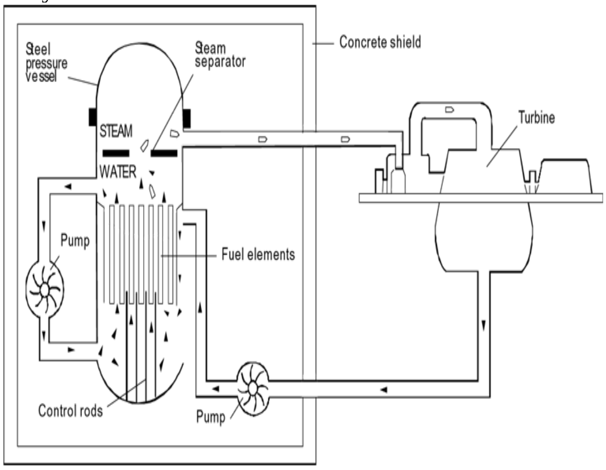
The secondary circuit is under less pressure and the water here boils in the heat exchangers which are thus steam generators. The steam drives the turbine to produce electricity, and is then condensed and returned to the heat exchangers in contact with the primary circuit.

IV. BOILING WATER REACTOR (BWR)

This design has many similarities to the PWR, except that there is only a single circuit in which the water is at lower pressure (about 75 times atmospheric pressure) so that it boils in the core at about 285°C. The reactor is designed to operate with 12-15% of the water in the top part of the core as steam, and hence with less moderating effect and thus efficiency there. BWR units can operate in load-following mode more readily then PWRs.



The steam passes through drier plates (steam separators) above the core and then directly to the turbines, which are thus part of the reactor circuit. Since the water around the core of a reactor is always contaminated with traces of radio nuclides, it means that the turbine must be shielded and radiological protection provided during maintenance. The cost of this tends to balance the savings due to the simpler design. Most of the radioactivity in the water is very short-lived*, so the turbine hall can be entered soon after the reactor is shut down mostly N-16, with a 7 second half-life

A BWR fuel assembly comprises 90-100 fuel rods, and there are up to 750 assemblies in a reactor core, holding up to 140 tonnes of uranium. The secondary control system involves restricting water flow through the core so that more steam in the top part reduces moderation.

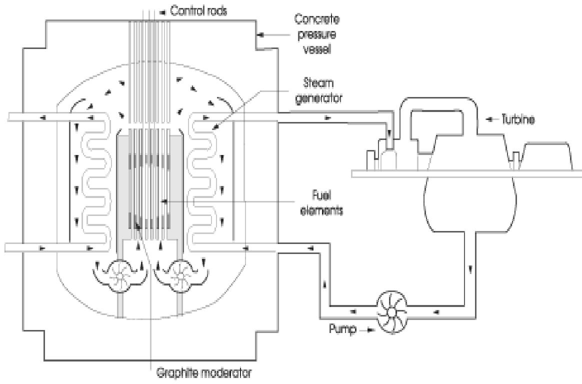
V. PRESSURISED HEAVY WATER REACTOR (PHWR OR CANDU)

The PHWR reactor design has been developed since the 1950s in Canada as the CANDU, and more recently also in India. PHWRs generally use natural uranium (0.7% U-235) oxide as fuel, hence needs a more efficient moderator, in this case heavy water (D2O). The PHWR produces more energy per kg of mined uranium than other designs with the CANDU system, the moderator is enriched (ie water) rather than the fuel, - a cost trade-off.The moderator is in a large tank called a calandria, penetrated by several hundred horizontal pressure tubes which form channels for the fuel, cooled by a flow of heavy water under high pressure in the primary cooling circuit, reaching 290°C. As in the PWR, the primary coolant generates steam in a secondary circuit to drive the turbines. The pressure tube design means that the reactor can be refueled progressively without shutting down, by isolating individual pressure tubes from the cooling circuit.

A CANDU fuel assembly consists of a bundle of 37 half metre long fuel rods (ceramic fuel pellets in zircaloy tubes) plus a support structure, with 12 bundles lying end to end in a fuel channel. Control rods penetrate the calandria vertically, and a secondary shutdown system involves adding gadolinium to the moderator. The heavy water moderator circulating through the body of the calandria vessel also yields some heat.

VI. ADVANCED GAS-COOLED REACTOR (AGR)

These are the second generation of British gas-cooled reactors, using graphite moderator and carbon dioxide as primary coolant. The fuel is uranium oxide pellets, enriched to 2.5-3.5%, in stainless steel tubes. The carbon dioxide circulates through the core, reaching 650°C and then past steam generator tubes outside it, but still inside the concrete and steel pressure vessel (hence 'integral' design). Control rods penetrate the moderator and a secondary shutdown system involves injecting nitrogen to the coolant.



The AGR was developed from the Magnox reactor, also graphite moderated and CO2 cooled, and one of these is still operating in UK to late 2014. They use natural uranium fuel in metal form. Secondary coolant is water

VII. LIGHT WATER GRAPHITE-MODERATED REACTOR (RBMK)

This is a Soviet design, developed from plutonium production reactors. It employs long (7 metre) vertical pressure tubes running through graphite moderator, and is cooled by water, which is allowed to boil in the core at 290°C, much as in a BWR. Fuel is low-enriched uranium oxide made up into fuel assemblies 3.5 metres long. With moderation largely due to the fixed graphite, excess boiling simply reduces the cooling and neutron absorbtion without inhibiting the fission reaction, and a positive feedback problem can arise, which is why they have never been built outside the Soviet Union.

VIII. ADVANCED REACTORS

Several generations of reactors are commonly distinguished. Generation I reactors were developed in 1950-60s and only one is still running today.

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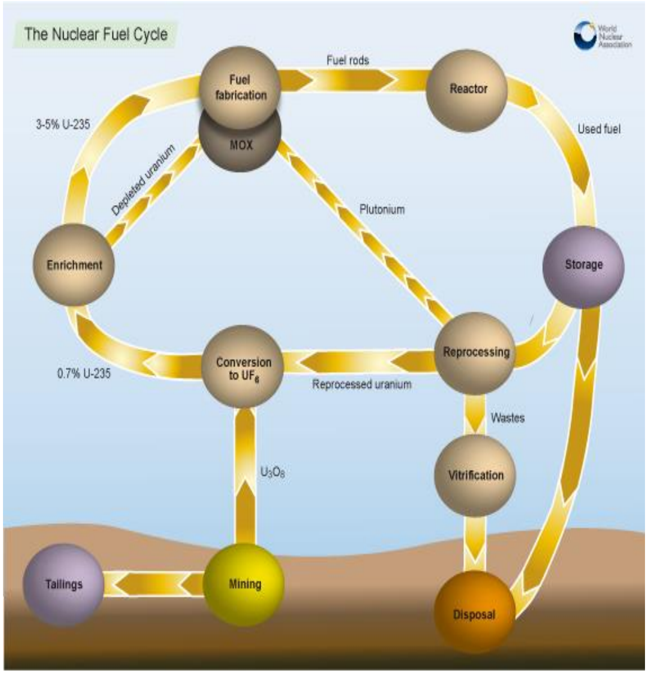
They mostly used natural uranium fuel and used graphite as moderator. Generation II reactors are typified by the present US fleet and most in operation elsewhere. They typically use enriched uranium fuel and are mostly cooled and moderated by water. Generation III are the Advanced Reactors evolved from these, the first few of which are in operation in Japan and others are under construction and ready to be ordered. They are developments of the second generation with enhanced safety.

IX. FAST NEUTRON REACTORS (FNR)

Some reactors (only one in commercial service) do not have a moderator and utilise fast neutrons, generating power from plutonium while making more of it from the U-238 isotope in or around the fuel. While they get more than 60 times as much energy from the original uranium



X. FUEL FABRICATION

Reactor fuel is generally in the form of ceramic pellets. These are formed from pressed uranium oxide (UO2) which is sintered (baked) at a high temperature (over 1400°C) a . The pellets are then encased in metal tubes to form fuel rods, which are arranged into a fuel assembly ready for introduction into a reactor. The dimensions of the fuel pellets and other components of the fuel assembly are precisely controlled to ensure consistency in the characteristics of the fuel.

XI. POWER GENERATION AND BURN-UP

Several hundred fuel assemblies make up the core of a reactor. For a reactor with an output of 1000 megawatts (MWe), the core would contain about 75 tonnes of low-enriched uranium. In the reactor core the U-235 isotope fissions or splits, producing a lot of heat in a continuous process called a chain reaction.

XII. USED FUEL

With time, the concentration of fission fragments and heavy elements formed in the same way as plutonium in the fuel will increase to the point where it is no longer practical to continue to use the fuel. So after 18-36 months the used fuel is removed from the reactor. The amount of energy that is produced from a fuel assembly varies with the type of reactor and the policy of the reactor operator.

When removed from a reactor, the fuel will be emitting both radiation, principally from the fission fragments, and heat. It is unloaded into a storage pond immediately adjacent to the reactor to allow the radiation levels to decrease. In the ponds the water shields the radiation and absorbs the heat, which is removed by circulating the water to external heat exchangers.

Used fuel is held in such pools for several months and sometimes many years. It may be transferred to naturally-ventilated dry storage on site after about five years.

There are two alternatives for used fuel:

- reprocessing to recover and recycle the usable portion of it
- Long-term storage and final disposal without reprocessing.

XIII. REPROCESSING

Used fuel still contains about 96% of its original uranium, of which the fissionable U-235 content has been reduced to less than 1%. About 3% of the used fuel comprises waste products and the remaining 1% is plutonium (Pu) produced while the fuel was in the reactor and not 'burned' then. Reprocessing separates uranium and plutonium from waste products (and from the fuel assembly cladding) by chopping up the fuel rods and dissolving them in acid to separate the various materials. It enables recycling of the uranium and plutonium into fresh fuel, and produces a significantly reduced amount of waste (compared with treating all used fuel as waste).

XIV. WASTES

Wastes from the nuclear fuel cycle are categorised as high-, medium- or low-level wastes by the amount of radiation that they emit. These wastes come from a number of sources and include:

- Low-level waste produced at all stages of the fuel cycle;
- Intermediate-level waste produced during reactor operation and by reprocessing;
- High-level waste, which is waste containing the highly-radioactive fission products separated in reprocessing, and in many countries, the used fuel itself. Separated high-level wastes also contain long-lived transuranic elements.

A. *Used fuel and separated wastes: final disposal*

At the present time, there are no disposal facilities (as opposed to storage facilities) in operation in which used fuel, not destined for reprocessing, and the waste from reprocessing, can be placed. In either case the material is in a solid, stable waste form.

Although technical issues related to disposal are straightforward, there is currently no pressing technical need to establish such facilities, as the total volume of such wastes is relatively small. Further, the longer it is stored the easier it is to handle, due to the progressive decrease of radioactivity.

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There is also a reluctance to dispose of used fuel because it represents a significant energy resource which could be reprocessed at a later date to allow recycling of the uranium and plutonium.

A number of countries are carrying out studies to determine the optimum approach to the disposal of used fuel and wastes from reprocessing. The general consensus favours its placement into deep geological repositories, about 500 metres down, initially recoverable before being permanently sealed.

B. Other Sources of Nuclear Fuel

In the 1990s uranium mines gained a competitor, in many ways very welcome, as military uranium came on to the civil market under a US-Russian agreement. Since then half of the uranium used for electricity in the USA has come from Russian military stockpiles, and worldwide about one sixth of the market has been supplied thus.

Weapons-grade uranium in stockpiles built up during 1950s and 1960s has been enriched to more than 90% U-235 and must be diluted about 1:25 or 1:30 with depleted uranium (about 0.3% U-235). This means that progressively, Russian and other stockpiles of weapons material

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