A CONCISE GUIDE TO ADVANCED NUCLEAR REACTORS AND SMR

An Online Continuing Education Course for Engineers

Course Number: R-4020

Credit: 4 Hours / 4 PDH / 4 CPD

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ABBREVIATIONS / ACRONYMS

ANL – Argonne National Laboratory
BWR - Boiling Water Reactor
CRVR – Congressional Research Service Report (R45706) –Advance Nuclear Reactors: Technology Overview and Current Issues.
DOE – U.S. Department of Energy
EIA – U.S. Energy Information Administration
EPA –U.S. Environmental Protection Agency
FHR – Fluoride Salt Cooled High Temperature Reactor
HTGR – High Temperature Gas Cooled Reactor
IAEA – International Atomic Energy Agency
INL – Idaho National Laboratory
LWR – Light Water Reactor
MWe – Megawatt Electrical
MWt – Megawatt Thermal
MSR – Molten Salt Cooled Reactor
NRC – U.S. Nuclear Regulatory Commission
PWR – Pressurized Water Reactor
ORNL – Oak Ridge National Laboratory
SFR – Liquid Sodium Cooled Fast Reactor
SMR – Small Modular Reactor
VHTR – Very High-Temperature Gas Cooled Reactor

1.0 Introduction

As of now - in the last quarter of 2024, the USA, with 94 operating commercial nuclear reactors at 54 nuclear power plants, is the largest nuclear electrical power producer in the world. Nuclear power plants provide about 18-20 % of the total electrical energy requirement in the USA (source: EIA).

The first commercial Nuclear Power plant in the USA was put into operation in 1957 in Shipping port, Pennsylvania.

The average age of U.S. commercial nuclear power reactors that were operational as of April 30, 2024, is about 42 years, the oldest being the 620 MW Nine Mile Point Unit 1 in New York State, which entered commercial service in December 1969 and the newest to enter service, is the 1114 MW Vogtle Unit 4 in Georgia that began commercial operation in April 2024 (source: EIA).

Most of the Nuclear Power plants in the USA came into operation in the 1970s-1980s. After that, there was a general slowing down of building new Nuclear Power Plants for various techno-economic reasons like high capital cost, long regulatory approval and construction time, high-cost overrun, and adverse public perception due to accidents like in Three Mile Island (USA 1979), Chernobyl (Ukraine 1986) Fukushima Daiichi (Japan 2011), etc., continuing uncertainty about long term solution of the problem of waste-disposal, competition due to U.S. shale gas revolution, etc. The 1114 MW Vogtle Unit 3 in Georgia came into operation in July 2023, about 7 years after the Watt Bar Unit-2 in Tennessee started operation in 2016. The construction of Vogtle unit-3 and 4 began in 2009, originally expected to cost $14 Billion, and begin commercial operation in 2016 (unit-3) and 2017 (unit-4). The plant ran into significant constriction delays and cost overruns. The total project cost is now estimated to be more than $30 Billion, i.e., more than double the original expectation (source: EIA).

The capital cost of nuclear power plants is relatively high. So, to be competitive, the capacities of nuclear power plants are also relatively high to achieve the economy of scale. Typically, a present-day nuclear power plant has a capacity of around 1000 MW or more.

After Vogtle unit-3 and 4, there is no upcoming conventional (also called "legacy") nuclear power plant in the USA. However, the characteristic of a nuclear power plant of being a source of dispatchable carbon-free base load power with a high capacity factor has led to the renewed interest in installing new plants to keep pace with the growing concern over global warming and ever-growing energy demand. At the World Climate Action Summit in Dubai, UAE, 20 countries, including the USA, Canada, France, Japan, Korea, UK, etc., issued a declaration that recognizes the key role of nuclear energy in achieving global net-zero, and pledged "to work together to advance a global aspirational goal of tripling nuclear energy capacity from 2020 by 2050, recognizing the different domestic circumstances of each Participant" (source: DOE).

It was felt that to meet the aforesaid requirement of de-carbonization together with meeting the ever growing energy demand, the existing fleet of nuclear plants should be utilized to the fullest extent together with installing new nuclear power plants. There were extensive efforts to renovate, repair, and upgrade the existing nuclear power plants in order to extend their operating life. NRC grants operating licenses for 40 years for new commercial nuclear reactors, which may be extended for 20 more years if applied for by the Owner. The period after the initial licensing is known as the " period of extended operation." Now, the NRC may grant another 20-year operating license extension (subsequent license renewal) for a total operational life of 80 years. Many of the present reactors are in the *extended period of operation* and some have applied for *subsequent license renewal* for 20 more years (source: NRC).

As for new nuclear plants, the idea of installing large legacy plants did not get much traction in the USA due to the experience of such plants incurring large capital costs, large and extended construction time, severe cost overrun, resulting in investment risk, etc. Instead, there was a lot of interest in Advanced Nuclear Reactors and Small Modular Reactors (SMR), which avoided most of the concerns mentioned. This was further encouraged by recent legislation for government subsidies for development and creating test plants of such new generation of nuclear reactors, as a part of the green energy initiative.

This course material focuses on these advanced Nuclear Reactors and Small Modular Reactors (SMR).

2.0 Recollecting the Basics

A nuclear power plant has two basic sections – the Nuclear Reactor, which generates Nuclear Energy by splitting the atom and harnesses the nuclear energy to generate heat energy, and an energy conversion system, consisting of a steam generator, steam turbine-generator, condenser, and other equipment, piping, etc. to convert the heat energy generated by the nuclear reactor to electrical energy.

The Reactor and the Energy Conversion System

The nuclear reactor generates heat energy from the nuclear energy in the atom. Nuclear energy can be extracted from atoms by two processes – Nuclear Fission and Nuclear Fusion. The process of Nuclear Fusion is still largely in the research stage; Nuclear Fission is the process utilized in all the present commercial reactors.

The Nuclear Fission process is explained in Figure 1. An atom of Uranium 235 (U^{235}), an isotope of uranium, the most widely used fuel in present commercial reactors, is hit by a Neutron and splits into two lighter elements and more neutrons and releases lots of energy. The neutrons, released at the collision, collide with other U^{235} atoms, setting up a nuclear chain reaction. The energy released by the Fission process is harnessed in the Reactors to generate heat energy.

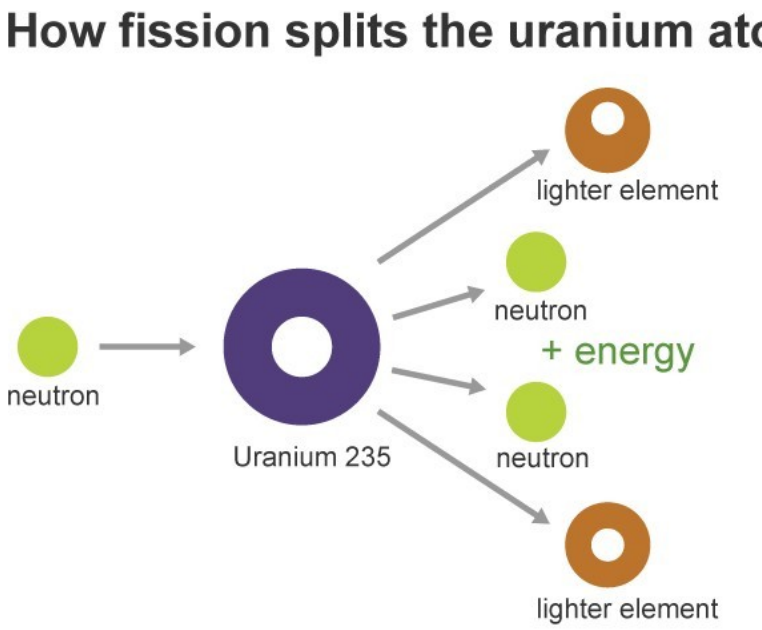


Figure 1 (source: EIA)

A conventional nuclear reactor (see fig-2 and 3) is typically made up of a reactor pressure vessel housing the CORE - where the nuclear fission takes place, the fuel assemblies, the coolant, the moderator, and the control rods along with the provision of conversion of nuclear energy (heat) to steam all enclosed in a containment structure.

Uranium fuel is processed into ceramic pellets and stacked into metal tubes (typically of Zirconium alloy), called Fuel Cladding, which forms the first barrier between the reactor coolant and the nuclear fuel pellets. The ends of these cladding tubes are sealed to form Fuel Rods. A bunch of such fuel rods makes a Fuel Assembly. The number of such fuel assemblies in a reactor depends on its power rating. The fuel rods are immersed in coolant and moderator. The coolant carries away the heat energy released by Nuclear Fission at the core to generate steam, and the moderator slows down the Neutrons produced by the fission process to sustain the chain reaction. In the conventional reactors, called Light Water Reactor (LWR), Light water (ordinary water) is used as both the coolant and the moderator. The Control rods are inserted into or retracted from the reactor core to reduce or increase the nuclear reaction depending on the load.

All commercial reactors in the USA, at present, are Light Water Reactors. There are two types of Light Water reactors – A Pressurized Water reactor (PWR) and a Boiling Water Reactor (BWR).

In the Pressurized Water Reactor (PWR) (Figure 2), the coolant water is pumped through the reactor core at high pressure to avoid boiling at the high temperature reached by absorbing the heat generated by nuclear fission. The heated water then passes through a heat exchanger (Steam Generator), located outside the reactor pressure vessel and inside the containment structure, to generate steam and pumped back to the core to be reheated again. The generated steam is fed to the steam turbine cycle operating in a separate closed cycle. In this system, the core coolant water cycle and the steam turbine cycle are different and interact only with the steam generator.

In the Boiling Water Reactor (BWR) (Figure 3), coolant water is pumped through the core, and steam is generated directly inside the reactor pressure vessel, absorbing the heat generated by nuclear fission. The steam is then fed to the power generation system, condensed, and pumped back to the reactor.

The majority of the commercial reactors in the USA are Pressurized Water Reactors.

Containment

Present-day nuclear plants are provided with large containment structures around and covering the reactor pressure vessel and steam generator to prevent accidental release of radiation.

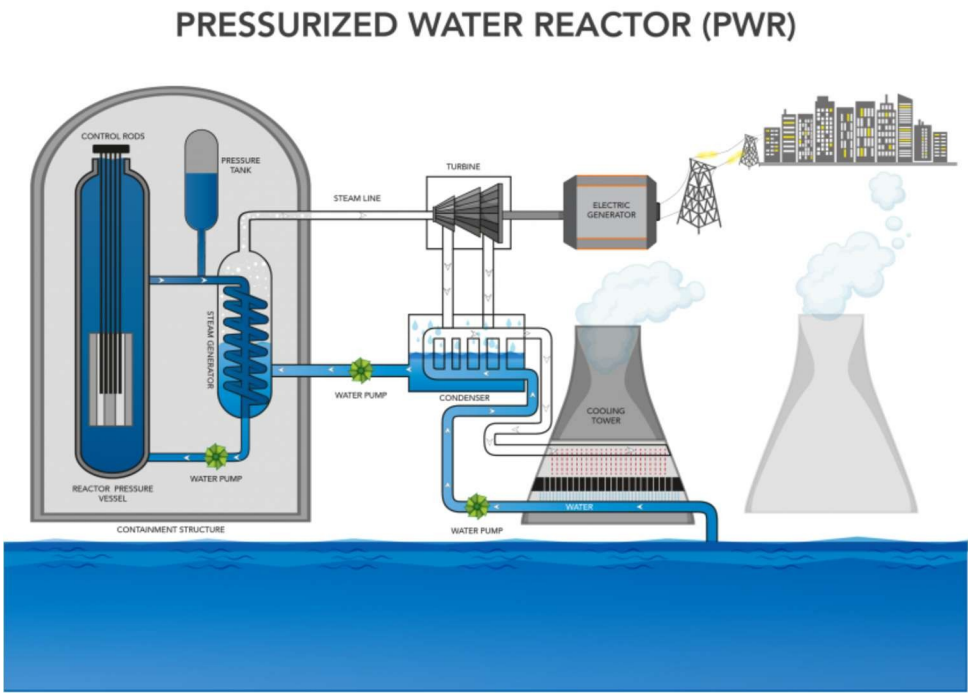
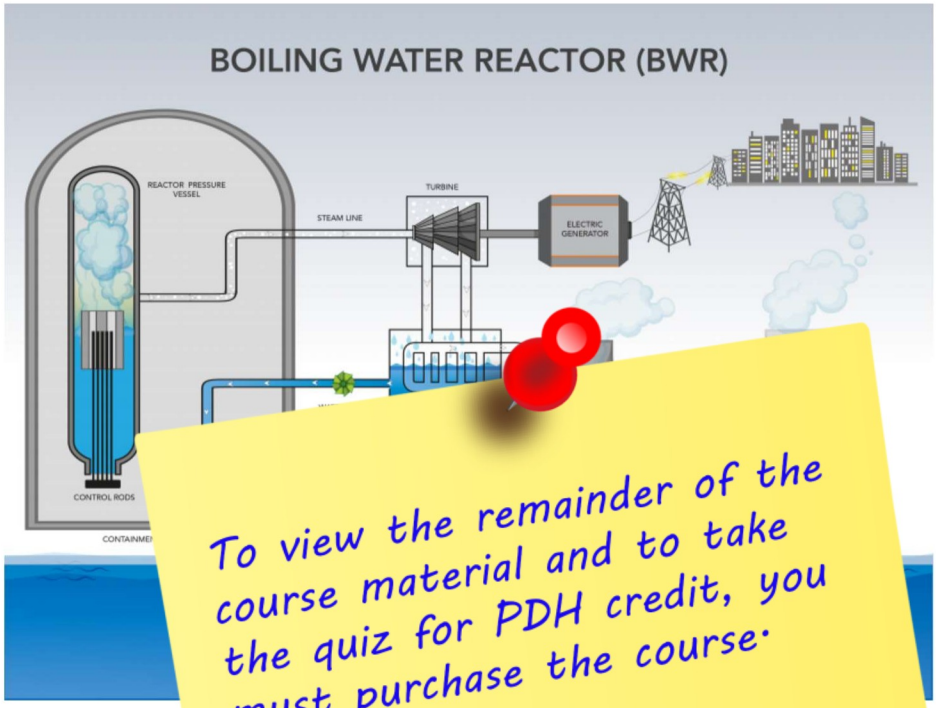


Figure 2 (Source: DOE)



3.0 The Fuel

Conventional Nuclear Fue

Uranium 235 (U^{235}), an isotope of ...ventional nuclear reactors in the USA.

When Uranium is mined, it consists of approximately 99.3% Uranium-238 (U^{238}) Isotope, 0.7% Uranium-235 (U^{235}), Isotope and <0.01% Uranium-234 (U^{234}) Isotope. Commercially, the U^{235} Isotope is enriched to 3 to 5% and is then further processed to create nuclear fuel.

Fuel burn up

To make it into nuclear fuel, Uranium ore is processed to increase the concentration of atoms that can participate in the chain reaction of the Fission process in the reactor, to release nuclear energy. In general, the higher the concentration of these atoms, the longer the fuel can sustain a chain reaction, and the longer the fuel remains in the reactor, the higher the burn-up.

So, burn-up is a way to measure how much uranium is burned in the reactor. It is the amount of energy produced by the uranium. Burn up is expressed in gigawatt-days per metric ton of Uranium (GWd/MTU). For current reactors, the burn-up is over 45 GWd/MTU (Source: NRC).