Chapter 2 – Introduction

In the history of mankind there have been several attempts at obtaining a sustainable source of energy. One of the major breakthroughs during the mid - 20th century was the splitting of an atom resulting in the concept of nuclear energy. 50 years and with many achievements our country has proven itself to be a major player in the nuclear market mainly due to major strides in reactor technologies.

2.1 Nuclear Reactors

A **nuclear reactor**, formerly known as an **atomic pile**, is a device used to initiate and control a self-sustained nuclear chain reaction. Nuclear reactors are used at nuclear power plants for electricity generation and in nuclear marine propulsion. Heat from nuclear fission is passed to a working fluid (water or gas), which in turn runs through steam turbines. These either drive a ship's propellers or turn electrical generators' shafts. Nuclear generated steam in principle can be used for industrial process heat or for district heating. Some reactors are used to produce isotopes for medical and industrial use, or for production of weapons-grade plutonium. As of early 2019, the IAEA reports there are 454 nuclear power reactors and 226 nuclear research reactors in operation around the world.

<u>Types of nuclear reactors:</u>

(a) Pressurized water reactors (PWR) [moderator: high-pressure water; coolant: high-pressure water]

These reactors use a pressure vessel to contain the nuclear fuel, control rods, moderator, and coolant. The hot radioactive water that leaves the pressure vessel is looped through a steam generator, which in turn heats a secondary (non-radioactive) loop of water to steam that can run turbines. They represent the majority (around 80%) of current reactors. This is a thermal neutron reactor design, the newest of which are the russian VVER-1200, japanese Advanced Pressurized Water Reactor, american AP1000, chinese Hualong Pressurized Reactor and the franco-german European Pressurized Reactor. All the United States Naval reactors are of this type.

(b) Boiling water reactors (BWR) [moderator: low-pressure water; coolant: low-pressure water]

A BWR is like a PWR without the steam generator. The lower pressure of its cooling water allows it to boil inside the pressure vessel, producing the steam that runs the turbines. Unlike a PWR, there is no primary and secondary loop. The thermal efficiency of these reactors can be higher, and they can be simpler, and even potentially more stable and safe. This is a thermal neutron reactor design, the newest of which are the Advanced Boiling Water Reactor and the Economic Simplified Boiling Water Reactor.

(c) Pressurized Heavy Water Reactor (PHWR) [moderator: high-pressure heavy water; coolant: high-pressure heavy water]

A Canadian design (known as CANDU), very similar to PWRs but using heavy water. While heavy water is significantly more expensive than ordinary water, it has greater neutron economy (creates a higher number of thermal neutrons), allowing the reactor to operate without fuel-enrichment facilities. Instead of using a single large pressure vessel as in a PWR, the fuel is contained in hundreds of pressure tubes. These reactors are fueled with natural uranium and are thermal neutron reactor designs. PHWRs can be refueled while at full power, which makes them very efficient in their use of uranium (it allows for precise flux control in the core). CANDU PHWRs have been built in Canada, Argentina, China, India, Pakistan, Romania, and South Korea. India also operates a number of PHWRs, often termed 'CANDU-derivatives', built after the Government of Canada halted nuclear dealings with India following the 1974 Smiling Buddha nuclear weapon test.

(d) Advanced Heavy Water Reactor (AHWR):

The **advanced heavy-water reactor** (AHWR) is the latest Indian design for a next-generation nuclear reactor that burns thorium in its fuel core. It is slated to form the third stage in India's three-stage fuel-cycle plan. This phase of the fuel cycle plan is supposed to be built starting with a 300MWe prototype in 2016.Bhabha Atomic Research Centre (BARC) set up a large infrastructure to facilitate the design and development of these Advanced Heavy Water reactors. Things to be included range from materials technologies, critical components, reactor physics, and safety analysis. Several facilities have been set up to experiment with these reactors. The AHWR is a pressure tube type of heavy water reactor. The Government of India, Department of Atomic Energy (DAE), is fully funding the future development, the current development, and the design of the Advanced Heavy Water Reactor. The new version of Advanced Heavy Water Reactors will be equipped with more general safety requirements. India is the base for these reactors due to India's large Thorium reserves; therefore, it is more geared for continual use and operation of the AHWR.

The proposed design of the AHWR is that of a heavy-water-moderated nuclear power reactor that will be the next generation of the PHWR type. It is being developed at Bhabha Atomic Research Centre (BARC), in Mumbai, India and aims to meet the objectives of using thorium fuel cycles for commercial power generation. The AHWR is a vertical pressure tube type reactor cooled by boiling light water under natural circulation. A unique feature of this design is a large tank of water on top of the primary containment vessel, called the gravity-driven water pool (GDWP). This reservoir is designed to perform several passive safety functions.

The overall design of the AHWR is to utilize large amounts of thorium and the thorium cycle. The AHWR is much like that of the Pressurized heavy water reactor(PHWR), in that they share similarities in the concept of the pressure tubes and calandria tubes, but the tubes' orientation in the AHWR is vertical, unlike that of the PHWR.

The AHWR's core is 3.5 m long and has 513 lattice locations in a square pitch of 225 mm. The core is radially divided into three burn up regions. The burn up decreases as it moves toward the external surface of the core. Fuel is occupied by 452 lattice locations and the remaining 37 locations are occupied by shutdown system-1. This consists of 37 shut-off rods, 24 locations are for reactive control devices which are consisted of 8 absorber rods (AR's), 8 shim rods(SR's), and 8 regulating rods (RR's). By boiling light water at a pressure of 7 MPa**,** heat is then removed. The main focus with this model is to get the total power and a coarse spatial power distribution within the core to be within certain degree of accuracy.

The reactor design incorporates advanced technologies, together with several proven positive features of Indian pressurised heavy water reactors (PHWRs). These features include pressure tube type design, low pressure moderator, on-power refueling, diverse fast acting shut-down systems, and availability of a large low temperature heat sink around the reactor core. The AHWR incorporates several passive safety features. These include: Core heat removal through natural circulation; direct injection of emergency core coolant system (ECCS) water in fuel; and the availability of a large inventory of borated water in overhead gravity-driven water pool (GDWP) to facilitate sustenance of core decay heat removal. The emergency core cooling system (ECCS) injection and containment cooling can act (SCRAM) without invoking any active systems or operator action.

The reactor physics design is tuned to maximise the use of thorium based fuel, by achieving a slightly negative void coefficient. Fulfilling these requirements has been possible through the use of PuO_2-ThO_2 MOX, and ThO_2-$^{233}UO_2$ MOX in different pins of the same fuel cluster, and the use of a heterogeneous moderator consisting of amorphous carbon (in the fuel bundles) and heavy water in 80–20% volume ratio. The core configuration lends itself to considerable flexibility and several feasible solutions, including those not requiring the use of amorphous carbon based reflectors, are possible without any changes in reactor structure.

2.2 Safety systems in nuclear reactors

2.2.1 Usage of FPGAs

A **field-programmable gate array** (**FPGA**) is an integrated circuit designed to be configured by a customer or a designer after manufacturing – hence the term "field-programmable". The FPGA configuration is generally specified using a hardware description language (HDL), similar to that used for an Application-Specific Integrated Circuit (ASIC). Circuit diagrams were previously used to specify the configuration, but this is increasingly rare due to the advent of electronic design automation tools.

FPGAs contain an array of programmable logic blocks, and a hierarchy of "reconfigurable interconnects" that allow the blocks to be "wired together", like many logic gates that can be inter-wired in different configurations. Logic blocks can be configured to perform complex combinational functions, or merely simple logic gates like AND and XOR. In most FPGAs, logic blocks also include memory elements, which may be simple flip-flops or more complete blocks of memory. Many FPGAs can be reprogrammed to implement different logic functions, allowing flexible reconfigurable computing as performed in computer software.

Contemporary field-programmable gate arrays (FPGAs) have large resources of logic gates and RAM blocks to implement complex digital computations. As FPGA designs employ very fast I/O rates and bidirectional data buses, it becomes a challenge to verify correct timing of valid data within setup time and hold time.

Floor planning enables resource allocation within FPGAs to meet these time constraints. FPGAs can be used to implement any logical function that an ASIC can perform. The ability to update the functionality after shipping, partial re-configuration of a portion of the design and the low non-recurring engineering costs relative to an ASIC design (notwithstanding the generally higher unit cost), offer advantages for many applications.

Some FPGAs have analog features in addition to digital functions. The most common analog feature is a programmable slew rate on each output pin, allowing the engineer to set low rates on lightly loaded pins that would otherwise ring or couple unacceptably, and to set higher rates on heavily loaded pins on high-speed channels that would otherwise run too slowly. Also common are quartz-crystal oscillators, on-chip resistance-capacitance oscillators, and phase-locked loops with embedded voltage-controlled oscillators used for clock generation and management and for high-speed serializer-deserializer (SERDES) transmit clocks and receiver clock recovery. Fairly common are differential comparators on input pins designed to be connected to differential signaling channels. A few "mixed signal FPGAs" have integrated peripheral analog-to-digital converters (ADCs) and digital-to-analog converters (DACs) with analog signal conditioning blocks allowing them to operate as a system-on-a-chip (SoC). Such devices blur the line between an FPGA, which carries digital ones and zeros on its internal programmable interconnect fabric, and field-programmable analog array (FPAA), which carries analog values on its internal programmable interconnect fabric.

2.2.2 Interlock

An interlock is a feature that makes the state of two mechanisms or functions mutually dependent. It may be used to prevent undesired states in a finite-state machine, and may consist of any electrical, electronic, or mechanical devices or systems. In most applications, an interlock is used to help prevent a machine from harming its operator or damaging itself by preventing one element from changing state due to the state of another element, and vice versa. Elevators are equipped with an interlock that prevents the moving elevator from opening its doors, and prevents the stationary elevator (with open doors) from moving. Although both are idiot proof strategies, an interlock should not be confused with a simple safety switch. For example, in a typical household microwave oven, the switch that disables the magnetron if the door is opened is not an interlock. Rather, it would be considered an interlock if the door were locked while the magnetron is on, and the magnetron were prevented from operating while the door is open. Interlocks may include sophisticated elements such as curtains of infrared beams, photo detectors, a computer containing an interlocking computer program, digital or analogue electronics, or simple switches and locks.

```
if(door_open==True)
{
  magnetron=false;
}
```

```
while(magnetron==True)
{
  door_open=false;
}
```

Above is a typical illustrative pseudo code differentiating between a safety switch and an interlock for a microwave door oven (system 1) and the magnetron operating (system 2) inside a microwave. The second code successfully manages to **isolate the two systems** although both codes logically infer the same.

Following is a generalized block diagram of an interlock w.r.t. its surrounding systems.

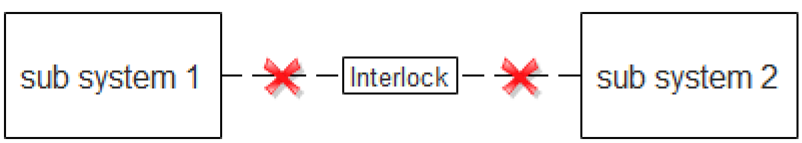

Figure 2.2.2 Interlock isolating two systems from each other