CHAPTER 1
INTRODUCTION

In this chapter a brief description of nuclear reactors and Indian nuclear power programme is given. The role of optimization is this context is also described.

The discovery of nuclear fission in 1939 can be regarded as the origin of the concept of nuclear reactors. In fission a neutron interacts with heavy nuclei such as $\text{U}^{235}$ to break it into two or more fragments. Hahn and Strassman showed that fission not only released a lot of energy but that it also released additional neutrons which could cause fission in other uranium nuclei and hence it can lead to self-sustaining chain reaction. Bohr soon proposed that fission was much more likely to occur in the $\text{U}^{235}$ isotope than in $\text{U}^{238}$ and that fission would occur more effectively with slow-moving neutrons than with fast neutrons. Fermi designed the first reactor in 1942. After that a series of power and research reactors were designed and operated successfully. Presently, about 16-17% of total world electricity requirement comes from nuclear power. Nuclear reactors can be classified based on the kinetic energy of the neutrons causing most of the fissions in the reactor. If the reactor contains a considerable proportion of moderator, the high energy of the fission neutrons will be rapidly decreased to the thermal value (around 0.025 ev) and such reactors are called thermal reactors. The light nuclei elements like light water, heavy water and graphite are used for moderation purpose. In the fast reactor no moderator is present and nearly all the neutrons causing fission have high energy (average values lie between 1 ev to 2 Mev). Fast reactor needs at least 20% enriched fissile material as a fuel. Thermal reactor which uses light water needs enrichment of $\text{U}^{235}$ to about 2 to 5 percent. The majority of the worldwide operating nuclear power plants are light water reactors; i.e. either pressurized water reactors (PWRs) or boiling water reactors (BWRs).

Another popular type is the Pressurized Heavy Water Reactor (PHWRs) [1]. There are more than 44 PHWRs operating in the world. PHWR uses Natural Uranium (NU) as fuel and heavy water as coolant and moderator. The use of heavy water moderator is the key to the PHWR system. Since heavy
water has much lower neutron absorption cross-section [2], it is possible to use NU as fuel. The PHWR can be operated without expensive uranium enrichment facilities. The relatively lower temperature and high density moderator results into sufficiently thermalized neutrons and hence a better fuel utilization [2, 3, 4, 5, 6, 7]. There are some drawbacks associated with PHWR also. PHWR needs a costlier heavy water in tons. The lower fissile content in NU necessitates the continuous online fueling requirement. The increased rate of refueling results higher volumes of spent fuel.

The Indian PHWR programme consists of 220 MWe, 540 MWe and 700 MWe units [1]. They constitute the first stage of the “Three-stage Indian Nuclear Power Programme”. These reactors can produce the Plutonium needed in the Second stage for the construction of Fast Breeder Reactors. The Third stage involves utilisation of Thorium to further multiply the power generation capability. The earliest PHWR units (RAPS-1 and RAPS-2) of India are of Canadian design (based on Douglas point). MAPS-1&2 design was evolved from RAPS-1&2, with modifications carried out to suit the coastal site requirement. With experience of design and operation of earlier units and indigenous R&D efforts, major modifications were introduced in NAPS-1&2. These units are the basis of standardized Indian PHWRs. The important features introduced in these units include: two diverse and fast acting shutdown systems, double containment of reactor building, water filled Calandria vault etc. The design of KAPS-1&2 was similar to that of NAPS units. The design of subsequent units i.e. KGS-1, KGS-2, RAPS-3, RAPS-4, RAPS-5, RAPS-6, KGS-3 and KGS-4 is of standard 220 MWe Indian PHWR design. TAPS-3 and TAPS-4 are medium size Indian PHWRs designed for 540 MWe electricity. The thermal power of standard 220 MWe PHWR is 756 MWth whereas, it is 129% more (i.e. 1730 MWth) for 540 MWe PHWR. Thermal power increases by 50% if one increases the total number of fuel channels from 306 to 392 and total number of fuel bundles in each channel (effective region) of the core from 10.1 to 12.0. For the rest 79% increase in thermal power, the fuel bundle design has been changed. In 220 MWe PHWRs 19 pin bundles are used whereas, in 540 MWe PHWR 37 pin bundles are used. With the 37 pin bundle about 98% more power can be extracted as compared to 19 pin bundle because of its lesser diameter. It is obvious that as 540 MWe PHWR is concerned, there is still about 19% margin on bundle power that can be utilized to increase the total reactor power. The successful operation of 220 and 540 MWe PHWRs forms the basis of designing higher capacity like 700 MWe PHWR. In the same core configuration as that of 540 MWe, the reactor total power has been increased by utilizing the margin available in bundle power. In the total 25% increase in reactor power, 18% is by using margin available
on bundle power and 7% is by more flattening. Extraction of additional heat is achieved by allowing boiling of coolant near the channel exit.

In the field of nuclear reactors, optimization problems are faced at various stages. A country has to make optimum choice of reactor types based on its resources. Optimization is needed in the detailed design of a particular type of reactor. This can involve design of fuel lattices, heat transfer system, power maneuvering, control system and so on. The objective can be of various types. The aim could be to save natural uranium, or maximize power production by Thorium, or reduce doubling period in a fast reactor, or employ proliferation resistant schemes. **The optimization schemes studied in this thesis are concerned with the design and operation of PHWRs.**

Fuel Management is a very important activity for continuous operation of PHWRs. It has a bearing on the two factors which are crucial to the Nuclear Power industry namely Safety and Economy. From the economy point of view, it is always desirable to draw maximum power from the reactor. For safety, the power distribution in a reactor should be such that the heat is safely removed. **The optimization of fresh core loading is addressed in this thesis.**

The reactors are equipped with regulation and protection systems so that they can be operated safely. The regulating system prevents any deviation from normal operation but if the deviation remains uncontrolled, the unwanted operational occurrences are eliminated by protection system (also called shutdown system). **Optimization of design of Thermal Power Measurement System (TPMS) and algorithm for flux map generation in On-line Flux Mapping System (OFMS), which are part of regulating system, is considered in this thesis.**

The solution of above optimization problems needs neutronic simulation of the full PHWR core and knowledge of the power distribution inside the reactor. In the chapter 2, a detailed description of Indian PHWR is given and the optimization problems studied in thesis are described in more detail. Chapter 3 gives the computational method [8, 9, 10, 11] employed for the neutronic simulation of PHWRs. Chapter 4 describes the optimization techniques in perspective. It may be mentioned that the problems having very large number of decision variables are often solved by Evolutionary Algorithms (EAs) [12]. EAs and Simulated Annealing are well known optimization methods [13, 14, 15, 16, 17] that have been used to solve various type of problems in science and engineering. The Simulated Annealing, Genetic Algorithm, Particle Swarm Optimization and Ant Colony Optimization have been extensively used to solve light water reactor fuel management and control design problems [13, 18, 19, 20, 21, 22].
In case of PHWR, however, the problem of generating fresh core loading pattern in PHWR has been often solved simply by manual trials and experience. The aim is to get sufficient power flattening by adding some Depleted Uranium or Thorium bundles so as to draw full power without violating safety features. The number of possible configurations is generally very large and manual trials may not yield solution close to optimum. The first significant improvement was made two decades ago by Balakrishnan and Kakodkar [23]. They used a gradient-based method. In the present thesis evolutionary algorithms are used for the first time for optimization of PHWR initial fuel loading. Two types of EAs namely Genetic Algorithm (GA) and Estimation of Distribution Algorithm (EDA) were tried. Chapter 5 describes the initial fuel loading problem in a 220 MWe PHWR. The EDA was found to be more efficient than GA. Chapter 6 is concerned with the use of estimation of distribution algorithm to solve initial core loading problem in 700 MWe PHWR. For the problem of finding optimum choice of instrumented channels for the design of Thermal Power Monitoring System, only EDA was tried and was found to work well as described in chapter 7. Chapter 8 describes the problem of optimization of computational scheme for flux mapping in which the decision variables are not too many and it is solved by explicitly trying the possible choices. Chapter 9 gives conclusion and scope for future work.