CHAPTER 2
OPTIMIZATION PROBLEMS IN PHWRs

In this chapter the design and operation of the Indian PHWR is described in some detail. Later on the specific optimization problems in Indian PHWRs studied in this thesis are described.

2.1. General Description of Indian PHWR

The Pressurized Heavy Water Reactor (PHWR) belongs to two categories: PHWR with moderator dump as a shutdown system and PHWR having shutoff rods and liquid poison addition for shutdown. The 220 MWe PHWR at RAPS and MAPS (RAPS#2, MAPS#1 and MAPS#2) have moderator dump as shut down system. The reactor is made critical by raising the moderator level in the reactor core. The standard 220 MWe PHWR (NAPS#1, NAPS#2, KAPS#1, KAPS#2, KGS#1, KGS#2, KGS#3, KGS#4, RAPS#3, RAPS#4, RAPS#5 and RAPS#6) uses two independent shutdown systems: 14 mechanical shutoff rods known as Primary Shutdown System (PSS) and 12 liquid poison tubes known as Secondary Shutdown System (SSS). The 540 MWe PHWRs at TAPS (TAPS#3 and TAPS#4) are also equipped with two independent shut down systems: 28 mechanical shutoff rods (SRs) and 6 horizontal tubes to mix the neutron poison in the moderator.

The PHWR is a horizontal tube type reactor (as shown in Fig.2.1) fuelled with Natural Uranium (NU) with heavy water as both coolant and moderator. The coolant is physically separated from the moderator by being contained inside the pressure tube where it is maintained at high temperature and pressure. The moderator heavy water is at a relatively low temperature and is unpressurized. The reactor core consists of 306 in 220 MWe and 392 in 540 MWe pressure tubes arranged along a square lattice pitch (22.86 cm in 220 MWe and 28.6 cm in 540 MWe). The fuel pins and the coolant are contained within these pressure tubes. The direction of coolant flow in adjacent channels is in opposite directions. The direction of the bundle movement (fuelling direction) is the same as that of the coolant flow, so that alternate channels are fuelled in opposite directions. In 220 MWe PHWRs, there are 12 fuel bundles along a fuel channel but only 10 remain in the active portion of the core. In 540 MWe PHWRs, there are
13 fuel bundles along a fuel channel but only 12 remain in the active portion of the core. Each bundle in 220 MWe PHWR is a 19-rod cluster of 49.5 cm length. Similarly each bundle in 540 MWe PHWR is a 37-pin cluster of 49.5 cm length.

The total reactor power is measured using Instrumented Channel power Measurement System (ICMS) in 220 MWe PHWRs. In ICMS 18 fuel channels are instrumented which measure inlet temperature, outlet temperature and flow and they are used to estimate total reactor power. For the purpose of reactor regulation in 220 MWe PHWR, there are 4 Adjuster Rods (ARs), 2 Regulating Rods (RRs) and 2 Shim Rods (2SRs). The prime difference between 220 MWe and 540 MWe PHWRs is the neutronic coupling. The 540 MWe reactor, being large sized, is loosely coupled and hence is prone to spatial flux/power oscillations during its operation. Hence, for reactor regulation, the core is logically divided into 14 zones. The zone powers also need to be monitored along with the total reactor power. There are 14 Zone Control Compartments (ZCC), 17 Adjuster Rods (ARs) symmetrically grouped into eight banks and 4 Control Rods (CRs). The zone powers are measured using zone control detectors (i.e. SPNDs). The zone powers measured by these small sized SPNDs can be corrected by ICMS zone powers or zone powers estimated by Flux Mapping System (FMS). For the measurement of reactor total power and zone powers, 44 fuel channels are instrumented to measure temperatures and flow. In FMS, there are 102 vanadium SPNDs. They are well distributed inside the reactor core. With the help of these vanadium detector readings detailed flux distribution in side core is obtained by flux mapping algorithm. The study related with ICMS and FMS is presented in the thesis.

The 700 MWe PHWR is in design stage and it has similar core dimensions of 540 MWe PHWRs [1]. In the same core configuration as that of 540 MWe, the reactor total power has been increased by utilizing the margin available in the fuel linear heat rating (LHR). The time average bundle power is 640 kW (LHR=40kW/M) and 790 kW (LHR=50kW/M) in 540 and 700 MWe PHWR respectively. In the total 25% increased in reactor power, 18% is by jacking up the flux/power profile (maximum time average channel power 5.5 MW in 540 MWe and 6.5 MW in 700 MWe) and 7% is by more flattening. Extraction of additional heat is achieved by allowing boiling of coolant near the channel exit. The regional over power trip (ROP) system is an additional feature in 700 MWe, whose function is to trip the reactor prior to the coolant dry out or fuel centre line melting in any region of the core. The ICMS like system is known as Thermal Power Monitoring System (TPMS) in 700 MWe. The PHT (Primary Heat Transfer) system in 220 MWe reactor core is in single loop but to reduce the effect of voiding in coolant
two radial half PHT loops are used in 540 MWe PHWR. The reactivity gain due to voiding in coolant has been further reduced in 700 MWe by using interleaved PHT system.

![Diagram of PHWR core and lattice]

**Figure 2.1: Typical PHWR core and its lattice**

### 2.2. Fuel Management

At the outset, it should be mentioned that there exist two distinct types of fuelling:

1) Batch fuelling
2) Continuous on-power fuelling.

The LWRs mostly use the Batch Fuelling. Owing to the use of slightly enriched Uranium, these reactors have substantial excess reactivity at the beginning of life. It can operate without any additional fuel for about a year or so [2]. At the end of such a period, the reactor is shut down and a pre-decided fraction (say 1/3) of the fuel is replaced by fresh fuel. The U-235 content in fresh fuel is about 2 to 5% whereas it less than 1% in the discharged fuel bundles. This procedure is repeated periodically throughout the life of the reactor. One has to arrive at the best possible distribution of the old and new fuel which gives the design power and also satisfies all the safety requirements. This activity is referred to as ‘Generation of Loading Pattern’. This is essentially a constrained combinatorial optimization
problem. The number of possible configurations is usually so huge that it is impossible to analyze each one of them.

The fuel management in PHWR is completely different than that in LWR. It employs the continuous on-power fuelling.

2.2.1. Three operating regimes of PHWR operation

The Pressurised Heavy Water Reactors (PHWR) use Natural Uranium (NU) fuel and have very little excess reactivity. They need continuous on-power fuelling. The fuelling procedure in this PHWR can be best explained by noting that the life-span of these reactors can be divided into three different stages:

i) Initial stage: from 0 days to about 150 days

The reactor operation starts with all fresh fuel bundles inside the reactor core. Since all the fuel bundles are fresh, the initial excess reactivity of the core is about 20 to 25 mk in hot operating condition. With this excess reactivity, available in the form of neutron poison in moderator, the reactor can operate up to about 150 FPD (full power days) without refueling of any fresh fuel bundle. The average burn-up in the core is low.

ii) Pre-equilibrium stage: from 150 days to about 600 days

At the completion of initial excess reactivity of the core, a proper fuel channel is selected and refueled. The 8 or 4 Bundle Shift Scheme (BSS) is used. This period is called pre-equilibrium stage of reactor operation. In the pre-equilibrium stage of reactor operation, since the relatively lower than design discharge burnup fuel bundles are thrown out of the core, the feed rate remains quite high.

iii) Equilibrium stage: from 600 days upto the life span of about 2 decades

After completion of about 600 FPD, the reactor enters the equilibrium stage of operation. The feed rate becomes constant. Almost every day, one of the channels is fuelled. The reactor operates about 95% of its life time in equilibrium phase.

The excess reactivity and average core burn-up for the three stages are graphically shown in Fig. 2.2 and 2.3 below.
Figure 2.2: The core excess reactivity vs FPD

Figure 2.3: The average in-core burnup vs FPD

An important feature of the equilibrium core is flattening of the power shape in both radial as well as axial direction. The axial flattening is achieved by fuelling adjacent channels in opposite directions. The radial flattening is achieved by considering two or three radial zones. The fuel discharge burn-up of inner region is higher than that of the outer region or in other words, fuelling is more frequent
in inner zone channels than outer zone channels. This helps in radial power/flux flattening so that more power can be extracted from the core than if the burn-up had been uniform throughout.

2.3. Specific Optimization Problems Studied in the Thesis

Different type of optimization problems are encountered during design and operation of PHWRs. At initial stage of reactor core, suitable loading pattern using fresh fuel bundles is needed for full power operation. With this loading the reactor can operate up to about 100 to 150 FPDs. In order to keep the reactor critical, it is necessary to do on-power fuelling in pre-equilibrium and equilibrium stage of PHWR. The fuelling is done in such a way that the flux/power remains flattened, so that the reactor can be operated at full power. The optimum choice of fuelling channel has to be made. Certain rejection rules are used to reduce the number of fuel channel candidates among which a suitable fuel channel has to be chosen. For example one can set a criterion that if the fuel channel discharge burnup is more than 75% of the design value, it will be considered for refueling. This is not a very large-sized problem and is being done at site on daily basis. Other problems related to PHWRs are design of TPMS and a suitable algorithm for FMS. The problems studied in thesis are listed below.

2.3.1. Loading pattern for initial stage of PHWR

The initial stage starts with the fresh reactor loaded with fresh NU fuel and needs no refueling for about 150 Full Power Days (FPD). However, during this period, the power peaking is much higher than in the equilibrium stage and hence the reactor has to be operated at lower power (~70%FP in 220 MWe, ~88%FP in 700 MWe). For economy, it is desirable to operate the reactor at close to Full Power. For this, some Thorium or Depleted Uranium (DU) bundles are loaded in the core. Thorium has zero fission cross section for thermal neutrons. DU has lower (from ~0.6wt% to ~0.3wt% U$^{235}$) fissile content than NU (0.7115wt% U$^{235}$). The locations of Thorium or DU bundles have to be chosen in such a way that following conditions are fulfilled:

1) Power peaking is reduced and maximum power can be drawn.
2) $K$-effective is maximized as far as possible.
3) Bundle power and channel power remain within limits.
4) The sufficient reactivity worth is possessed in the shut-down devices.

The main difficulty in deciding best fresh core loading pattern is that the total number of possible arrangements of NU and Thorium/DU bundles can be extremely large. For example: there are 306 fuel
channels and each channel contains 12 fuel bundles. Thus there are 306×12=3672 fuel bundle locations. Suppose one uses 30 Thorium bundles to obtain the desired level of flux/power flattening, this can be done in $^{3672} \text{C}_{30}$ ways (approximately $10^{75}$). In order to choose the best configuration, a brute force approach of trying all possible combinations is absolutely impossible because such a large number of diffusion calculations cannot be carried out even with the best supercomputer in the world.

The problem of determining fresh core loading pattern is solved here using a novel approach based on evolutionary algorithms.

2.3.2. Selection of instrumented channels for thermal power measurement system

There are 392 horizontal fuel channels in 700 MWe PHWR. It is necessary to select ~44 fuel channels (out of 392) for keeping instrumentation to measure flow and temperature of coolant. The selection of instrumented channels is to be made such that the average of power values measured by them in terms of per unit basis represents the true zone-wise and global powers fairly accurately. This should be possible for a large number of reactor configurations that can occur because of the movement of reactivity devices in the core. This capability is useful to make the TPMS more accurate means to measure the reactor bulk power and zone powers. The selection of 44 fuel channels for instrumentation is an optimization problem which has to satisfy the following constraints:

1. Total 44 numbers of channels should be selected and thus 11 numbers of channels should be there in each of the four sets of fuel channels.

2. The channels which have been selected for instrumentation should not be symmetric about X-axis.

3. Nowhere a gap of 4 pitch × 4 pitch or more should be left without a instrumented channel.

4. Each Zone Control Detector (ZCD) should have minimum two ICs at nearby location.

The problem of selecting instrumented channels for Thermal Power Measurement System is solved here using evolutionary algorithm.

2.3.3. Optimization of flux mapping algorithm for flux map generation

There are 102 vanadium self powered neutron detectors (SPNDs) in 700 MWe PHWR. They are well distributed inside the reactor core. With the help of these detector readings, one has to continuously estimate the detailed power distribution inside the reactor. This is achieved by the so-called Flux Mapping System (FMS). Apart from detector readings, the FMS makes use of the fact that flux shape is
governed by neutron diffusion theory. A detailed flux map is created by FMS every two minutes. It is used to calibrate the zonal detectors so that they correctly reflect the zonal powers. The maximum bundle power and channel power are also estimated to take corrective action if necessary.

The objective of FMS can be achieved by various algorithms. The computation by FMS has to be carried out every 2 minutes. Hence, the calculation should be fast enough. The resultant flux map is used for reactor regulation and to monitor channel powers and bundle powers. Hence, the calculation should be fairly accurate. These two requirements conflict with each other. Hence, an optimum choice has to be made from amongst the various computational algorithms suggested for this purpose. Some of the algorithms are based on modal method. In such methods, the number of modes needs to be optimized.

Here, apart from studying existing algorithms, a hybrid algorithm is suggested as an optimum choice.