GENERAL CONCEPTS

INTRODUCTION

This part of the course aims at giving the student an understanding of the actions of the Reactor Regulation System (RRS). It is based on the specific RRS of the CANDU-6 reactor. There exists marked differences between different reactor types, because of technological advances, and the philosophy of the designer groups. However, once a given RRS is understood, it is not very difficult to understand the variations for other reactors.

We will not delve on control theory in this part of the course. We will not determine why specific values of some gains for example have been chosen within different control algorithms. Such an approach is necessary when a new regulating system is being designed, and it is the subject of many specialized studies. As far as we are concerned, it is more important to develop the ability to predict and understand the behavior of an existing complex system, rather than build an entirely new control system.

Furthermore, in order to limit the description complexity, the control algorithms well be described in their normal operating conditions, for example for reactor powers ranging between about 1% Full Power and 100% FP. We will stay away from powers of 0.000001% FP and the special control modes necessary in these circumstances. Similarly, approach to critical and the special start-up instrumentation needed for it, will not be discussed in this course.

OBJECTIVES OF THE REACTOR REGULATING SYSTEM

The Reactor Regulating System (RRS) has many functions and aims, and many objectives simultaneously. The reactor itself produces all the energy of the power plant. It is thus very important to keep the 2050 MWth that are being generated under close surveillance.

In normal conditions, the regulating system aims, among other things, to maintain the reactor critical. It will thus have to compensate the different phenomena that tend to make the core super-critical or sub-critical.

One of the main task of the regulating system will then consist in maintaining the reactor power at a level fixed by the operator, while taking into account the status of all the plant systems. It goes without saying that a reactor that could not maintain power, i.e. an unstable core, would be of no practical interest, because public safety could not be ensured or the desired constant electrical energy output would be unachievable.

Another regulating system function is to adequately maintain the power distribution in the core. In fact, the CANDU-6 is divided into fourteen control zones; each of these zones has a target power, determined by the designer. This is to prevent negative effects, on the fuel for example, of having high powered zones neighboring zones at low power, the total power remaining constant. When power tilts occur, corrective measures are immediately taken, automatically, to prevent them from developing.

Another task of the regulating system is to determine and prevent, if possible, too fast variations of different parameters. This is to prevent spurious shutdown system activation. Shutdown systems are designed to rapidly stop the fission reaction in the core; this is to ensure public safety. They should not be solicited by events induced by normal regulation.

The regulating system also permits to obtain much information about the reactor, by posting measured or calculated parameter values, or by emitting alarms, when certain parameter levels are attained. The regulating system also permits changing the values of different parameters by following operating procedures. The man-machine interface permits the operator to do this with relative ease.

SPACE-TIME EFFECTS

The only way to predict the dynamic behavior of a nuclear reactor during transients, and to obtain a final stable state, is to utilize the methods of space-time kinetics coupled to thermal hydraulics in three dimensions. Such tools exist, with different levels of complexity for the purposes of safety calculations, design calculations, or training simulators.

Point kinetics is widely used to understand the behavior of a nuclear reactor, reduced (theoretically) to a single point. The assumption here is that the spatial shape of the neutron flux does not change during transients. The most important parameter in point kinetics is the reactivity, and reactivity appears in most discussions concerning core dynamics; we will not escape using it in this course. We should keep in mind that reactivity is not directly observable or measurable, and by consequence, reactivity per se is not taken into account by RRS. The concept of reactivity is used to give explanations in a quasi quantitative manner of reactor behavior. It is also used to compare relative efficacy of absorbing devices.

This being said, a nuclear reactor operated at a non-zero power level undergoes many different perturbations continually. The fuel, when exposed to neutrons suffers variations in absorption and production rates. This comes from fission product evolution; fission products can also be fissile elements themselves. The exact distribution of these fission products depends on the flux history to which the fuel has been exposed. This is referred to as fuel burn-up. A variation in the level of the liquid zone controllers is required to compensate for this. We say that the variation in reactivity due to burn-up of the fuel is compensated in the other direction by the reactivity of the zone controllers. Burn-up effects are mostly global and affect almost identically all control zones.

When fuel in a reactor channel reaches the end of its useful life in the core, it is replace by new fuel. These refuelings, numbering about two per day, generate local effects tending to increase power, which has to be compensated if total power is to be maintained at a constant value.

Xenon, which is a very strong absorber of thermal neutrons, causes particular problems to the operation of a nuclear power plant. First, during power maneuvers, Xenon will tend to increase the effect of the maneuver: if power is being reduced, Xenon will make it reduce further, and conversely, if power is increased, Xenon will make it increase even more. This is a global phenomenon. Furthermore, a local power variation will induce oscillations in the Xenon concentration, with a period of about twenty four hours; RRS will have to compensate adequately to prevent these oscillations.

Thermal hydraulic feedback effects, such as density, void and temperature of coolant, as well as fuel temperature and moderator temperature generate both local and global effects which will have to be compensated as well.

CONTROL METHOD

The control of the reactor is based essentially upon observable variables, such as flux detector readings, temperature, pressure, flow, level and position "detectors". These parameters are processed electronically (amplified, filtered) and sent to the control computers. The different control algorithms in turn read the values of these parameters, as well as the results of the calculations performed by the algorithms themselves, and by their programmed logic, determine the desired positions of the different devices (in a general sense). Changes in setpoints are sent for example to the zone controllers, the adjuster rods, the absorber rods, to the addition system of boron and gadolinium. The center of all these activities is the control room, which is divided into different areas, or panels, reporting specific information on the main systems of the power plant.

Reactor control and the man-machine interface are executed within the control computers, numbering two, named DCCX and DCCY ("Digital Control Computer"). These two computers, X and Y, are identical and perform the same calculations. Normally, the X computer performs the actual control. If X fails, then Y would automatically take this actual control.

REACTOR REGULATING SYSTEM

The control of the reactor is performed by a computer program residing in DCCX (and also in DCCY). This program is known as RRS. This program is the entity which will be studied in this course.

RRS is really made up of many components, of which the most important ones are:

- Program MCP: Power Measurement and Calibration
- Program CEP: Power Error Calculation
- Program CBL: Zone Level Control
- Program CBC: Adjuster Control
- Program CBS: MCA Control
- Program FLU: Neutron Flux Mapping
- Program BCP: Power Setback
- Program EBA: Shut-off rod removal

Each of these eight programs is in turn divided into two parts. There is a slow part, executed every two seconds, and a fast part, executed each half second. The collection of the slow parts is known as Slow Regulation of the Reactor (SRR). The collection of the fast parts is known as Fast Reactor Regulation (FRR). The one exception to this rule is the FLU program, whose complete execution is so long that it is only partially executed at each forty seconds, and completed every two minutes.

The sequence of execution is determined by an executive program, and is not always done in the same order. It is instead determined by the relative importance of the different tasks to beaccomplished within the remaining time window.

There exists another program, Reactor Stepback, which is not strictly part of the reactor regulating system. It is normally executed every 0.5 second, but when acting on devices, it is executed every 0.25 second. Reactor Stepback is used to rapidly insert the mechanical absorbers into the core when certain undesirable conditions appear in the power plant or the core.

SHUTDOWN SYSTEMS

We note that there are two shutdown systems:

- **shutdown system #1, SDS1, which acts by quickly inserting 28 shutoff rods into the core**
- **shutdown system #2, SDS2, which acts by adding liquid poison at high pressure into the moderator**

Each of these two systems are completely independent of each other, and independent of the regulating system. There is total separation of the protection functions and the regulation functions. Each of SDS1 and SDS2 is designed to stop quickly energy production in the core in all circumstances. The instrumentation connected to the shutdown systems is diverse in nature, being made of in-core flux detectors, but also of flow, pressure and temperature detectors. The self powered in-core platinum detectors make up the Regional Overpower Protection system (ROP). ROP is designed to prevent any fuel channel to attain Critical Heat Flux (related to the boiling crisis) during postulated loss of regulation accidents. This system will be discussed later in this course.

FLUX DETECTORS

Three neutron detector types are used to perform regulation and protection of the core. These are ion chambers, Platinum detectors, and Vanadium detectors.

Ion chambers are characterized by fast response to any change of power. However, they would not last long in the intense neutron fields found in the core. They are thus located near the periphery of the core, by the external boundary of the reflector.

Platinum detectors react quickly to neutron flux variations. They are also sensitive to gamma fields, which are produced in great intensity in the core. The response characteristics of these detectors vary in a complex way with time. Before irradiation, they have a prompt response giving about 84.5% of the total signal, and delayed response with components of widely different time constants making up the remaining 15.5%. At very low reactor power, a residual signal of about 2% and of very long time constant dominates the signal. Thus these detectors do not give reliable measurements at low power.

Vanadium detectors are sensitive only to neutrons, for all practical purposes. However, the nuclear reaction responsible for the detector signal, is a beta disintegration with a 225 second half life following a neutron absorption in the Vanadium. The detector thus reacts very slowly to changes in neutron flux.

Therefore measurements combining the responses of these three detector types are used in regulation and protection tasks over a wide power range.

DETECTORS FOR REACTOR CONTROL

3 Ion Chambers

Their signals are used for measuring low powers, when the reactor is in such a state. The logarithmic rate of change of the signals ("log rate") is also used in certain algorithms, since their response is essentially instantaneous.

28 Platinum Detectors

The 28 Platinum detectors are grouped by two, forming essentially 14 detector assemblies. Each of these 14 assemblies is associated with a control zone. Their signals play a fundamental role for all the regulating system, especially to modulate the movement of the zone controllers.

102 Vanadium Detectors

Vanadium detectors are distributed everywhere in the core. They are used mainly for flux mapping purposes. They are used also to correct the zonal powers measured by the 14 Platinum detector assemblies.

SAFETY DETECTORS: SDS1

3 Ion chambers

The logarithmic rate of change of these ion chambers will fire SDS1 when it reaches the equivalent of 10% per second. Their logarithmic signals ("log power") are also used to condition the firing of SDS1 at low power.

34 Platinum Detectors

They are quite uniformly distributed in the core, and constitute the SDS1 part of the ROP system. They will fire SDS1 if their trip set point (about 122.4%) is reached.

SAFETY DETECTORS: SDS2

Ion chambers

The logarithmic rate of change of these ion chambers will fire SDS2 when it reaches the equivalent of 15% per second. Their logarithmic signals ("log power") are also used to condition the firing of SDS2 at low power.

23 Platinum Detectors

They are quite uniformly distributed in the core, and constitute the SDS2 part of the ROP system. They will fire SDS2 if their trip set point (about 122.4%) is reached.

REACTIVITY DEVICES FOR REACTOR CONTROL

14 liquid zone controllers

We find one of these per control zone, hence 14 all. They are contained in 6 vertical assemblies. They contain light water, an absorber compared to the heavy water of the moderator and coolant. Their level is changed in order to keep at constant values the total reactor power as well as the power of the individual zones. The levels are thus being changed continuously. By design, they are always in the core.

21 adjuster rods

They are made of stainless steel, sometimes of cobalt 59. They provide operating margin against Xenon. They also flatten the spatial flux distribution. They are normally in the core. They can be removed sequentially from the core by RRS under specific conditions that we will examine in detail later.

4 mechanical control absorbers rods

They are made of stainless steel and Cadmium, and are very strong absorber of thermal neutrons. They are normally out of core. They can be inserted by RRS or Reactor Stepback under certain conditions.

Boron and Gadolinium

These are soluble poisons which may be added in small quantities to the moderator, either manually or automatically. A small quantity of boron is normally in the moderator in order to provide a slight flexibility to the time interval between refuelings.

REACTIVITY DEVICES FOR REACTOR SAFETY

28 shutoff rods

These rods constitute the method of action of SDS1 when it is solicited. Made of cadmium sandwiched between two layers of stainless steel, they are strong thermal neutron absorbers. Of course, they are normally outside of the core.

Gadolinium

Concentrated Gadolinium nitrate in 6 high pressure tanks constitute the action method of SDS2. Highly absorbing, it is also very difficult to remove from the moderator, which is performed with ion exchange resins. This is a process which takes more than 24 hours to complete.