SESSION 2:

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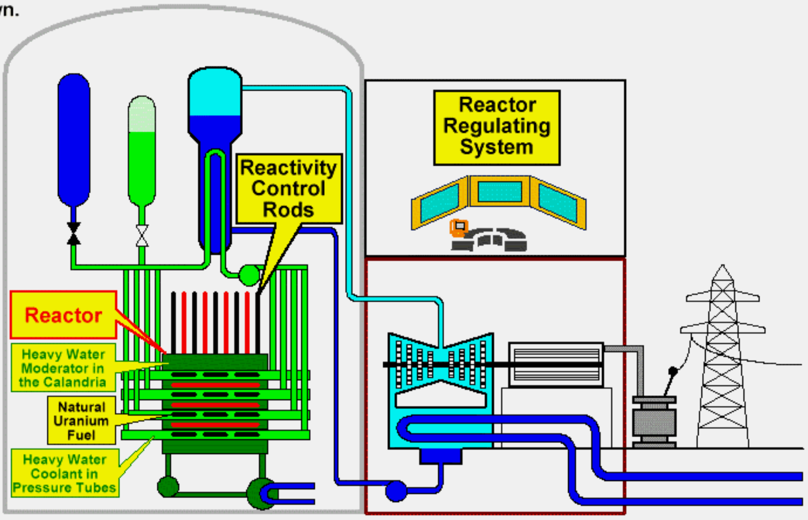
1. INTRODUCTION

The second session deals with the physical layout, main types of equipment, instrumentation and control algorithms used in the Reactor and the Reactor Regulating Systems. Many of the fundamental features that distinguish CANDU reactors from other types of nuclear electric facilities are highlighted in this session, such as the use of natural uranium fuel bundles, the horizontal calandria and pressure tube design, the use of the heavy water as moderator and coolant, the use of light water reactivity control, bulk versus spatial control, and reactor shutdown.



2. CANDU REACTOR ASSEMBLY – FUNCTIONAL REQUIREMENTS

The diagram illustrates many of the essential features of the CANDU reactor:

- the large horizontal cylinder shaped Calandria that contains the low pressure Moderator;
- the Pressure Tubes that traverse the Calandria from one end to the other and hold the fuel and the high pressure heavy water coolant, and allow for on-line refuelling;
- the Reactivity Control mechanisms, Shutdown Rods and associated vertical in-core flux measuring devices that penetrate the Calandria from the top;
- the Ion Chambers, horizontal in-core flux measuring devices and the second reactor shutdown system’s liquid poison injection nozzle assemblies that penetrate the Calandria from the side;
- the end shields and the concrete walls of the vault that provide both structural support and radiation shielding.

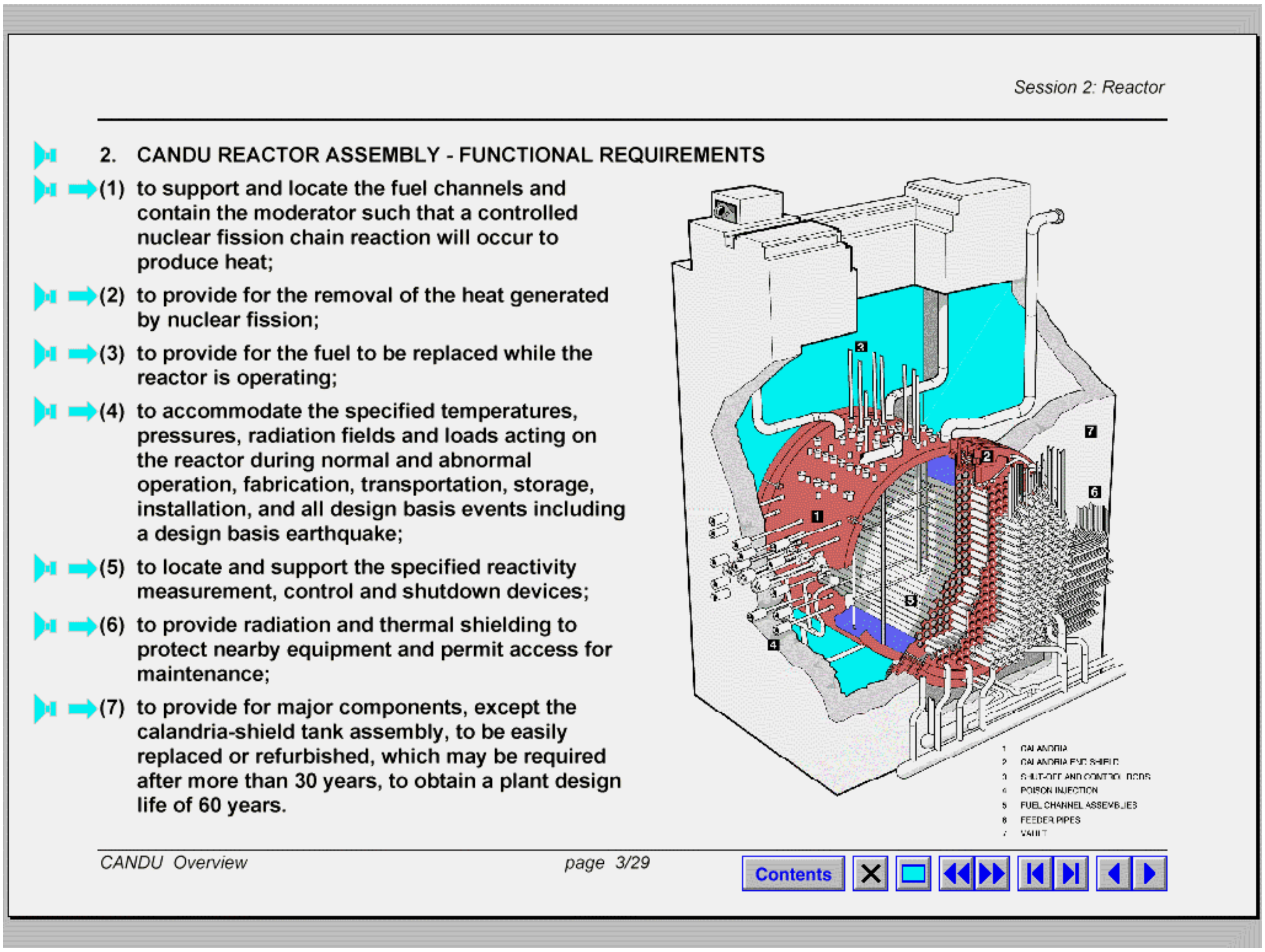
(1) The calandria is the main structural component to hold the fuel channels and to contain the moderator such that a controlled nuclear fission chain reaction will occur to produce heat. The Calandria shell is closed and supported by the End Shields at each end. The fuel channels are supported principally by the End Shields. The Calandria and the End Shields are themselves supported by the walls of the Reactor Vault.

(2) The heat generated in the fuel by nuclear fission is removed by the pressurized heavy water coolant that flows around and through the fuel bundles. Each fuel channel holds 12 fuel bundles. At either end, each pressure tube is connected by a feeder pipe to the respective header of the main heat transport system. The flow of coolant in adjacent fuel channels is in opposite directions, i.e. the flow through the core is bi-directional. The CANDU 6 reactor has 380 fuel channels, the CANDU 9 reactor has 480.

(3) At both ends of the fuel channels the zirconium pressure tubes are connected to stainless steel end fittings, which provide mechanical connections for the fuelling machines. The on-line refuelling system uses two identical fuelling machines, which are attached to the ends of the channel to be refuelled. One machine inserts new fuel at one end of the channel and the second machine removes irradiated fuel at the other end. The complete refuelling operation of a channel is achieved by remote control while the reactor is operating.

(4) The Calandria vessel is made of stainless steel and is usually fabricated at a significant distance from the power plant site. Its design has to accommodate the specified range of temperatures, pressures, radiation fields and loads acting on it during fabrication, transportation, storage, installation, normal and abnormal operation, and all design basis events including earthquakes. Installation of the various equipment, such as the pressure tubes, reactivity mechanisms and flux detectors takes place at the power plant site. The concrete vault that houses the calandria and all related reactor components are built during the construction of the plant, and must also withstand a design basis earthquake.

(5) The vertical and horizontal reactivity control devices, both for reactor regulation and shutdown, and the neutron flux detector assemblies are positioned in the Calandria. They are inside guide tubes that pass through the thimbles and in between the calandria tubes, and are attached at the bottom of the Calandria.



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2. CANDU REACTOR ASSEMBLY - FUNCTIONAL REQUIREMENTS

(1) to support and locate the fuel channels and contain the moderator such that a controlled nuclear fission chain reaction will occur to produce heat;

(2) to provide for the removal of the heat generated by nuclear fission;

(3) to provide for the fuel to be replaced while the reactor is operating;

(4) to accommodate the specified temperatures, pressures, radiation fields and loads acting on the reactor during normal and abnormal operation, fabrication, transportation, storage, installation, and all design basis events including a design basis earthquake;

(5) to locate and support the specified reactivity measurement, control and shutdown devices;

(6) to provide radiation and thermal shielding to protect nearby equipment and permit access for maintenance;

(7) to provide for major components, except the calandria-shield tank assembly, to be easily replaced or refurbished, which may be required after more than 30 years, to obtain a plant design life of 60 years.

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(6) In the axial direction of the Core, radiation and thermal shielding is provided by the End Shields. Each End Shield consists of an inner and outer tubesheet, which are joined by lattice tubes and a peripheral shell. The space inside the End Shield is filled with steel balls and ordinary water. The water is circulated through a cooling system to remove the absorbed heat.

In the radial direction, light water is used to provide shielding, in addition to the vault walls. For CANDU 6 the vault itself is filled with water. For CANDU 9 a Shield Tank, which surrounds the Calandria and is connected to the End Shields contains the light water for both thermal and biological shielding.

The shielding is designed to allow personnel access to the reactor face once the reactor has been shut down.

(7) The reactor assemblies are designed to allow all the major components to be easily replaced or refurbished during the extended (up to 60 years) operating life of the reactor. Such components include all the reactor control and shutdown mechanisms, the flux detectors, the pressure tubes, the feeder pipes, but not the calandria-shield tank assembly.

2.1 CANDU 9 REACTOR ASSEMBLY

This diagram shows additional details of the reactor assembly as compared with the figure on the previous page. Also note that this diagram illustrates a CANDU 9 reactor assembly: it has a shield tank, and the vault contains air, while the CANDU 6 Reactor Assembly shown on the previous page did not have a shield tank, but instead had the reactor vault filled with water.

(1) The arrows point to the six walls that form the vault: above and below, behind, in front of and on both sides of the reactor. The approximate dimensions of the CANDU 9 reactor vault are: 20 m high, 20 m wide and 12.5 m deep

(2) The reactivity mechanism deck holds all the flux measuring and controlling devices that penetrate the Calandria from above the reactor. The in-core vertical flux detectors measure the flux distribution in the core for both control and protection purposes. The vertical reactivity control devices include the different types of reactor control rods and the reactor shutdown rods.

(3) There are horizontal flux measuring devices and reactivity control units that penetrate the Calandria from the side. Arrow (a) points to one of the liquid poison injection nozzle assemblies of the second reactor shutdown system, which are used for the rapid shutdown of the reactor by the injection of liquid poison into the moderator. Arrow (b) points to one of the Ion Chamber assemblies, each of which measures the flux for the purpose of both regulation and protection. Arrow (c) indicates one of the horizontal in-core flux detector assemblies, used to provide flux measurement for the second shutdown system.

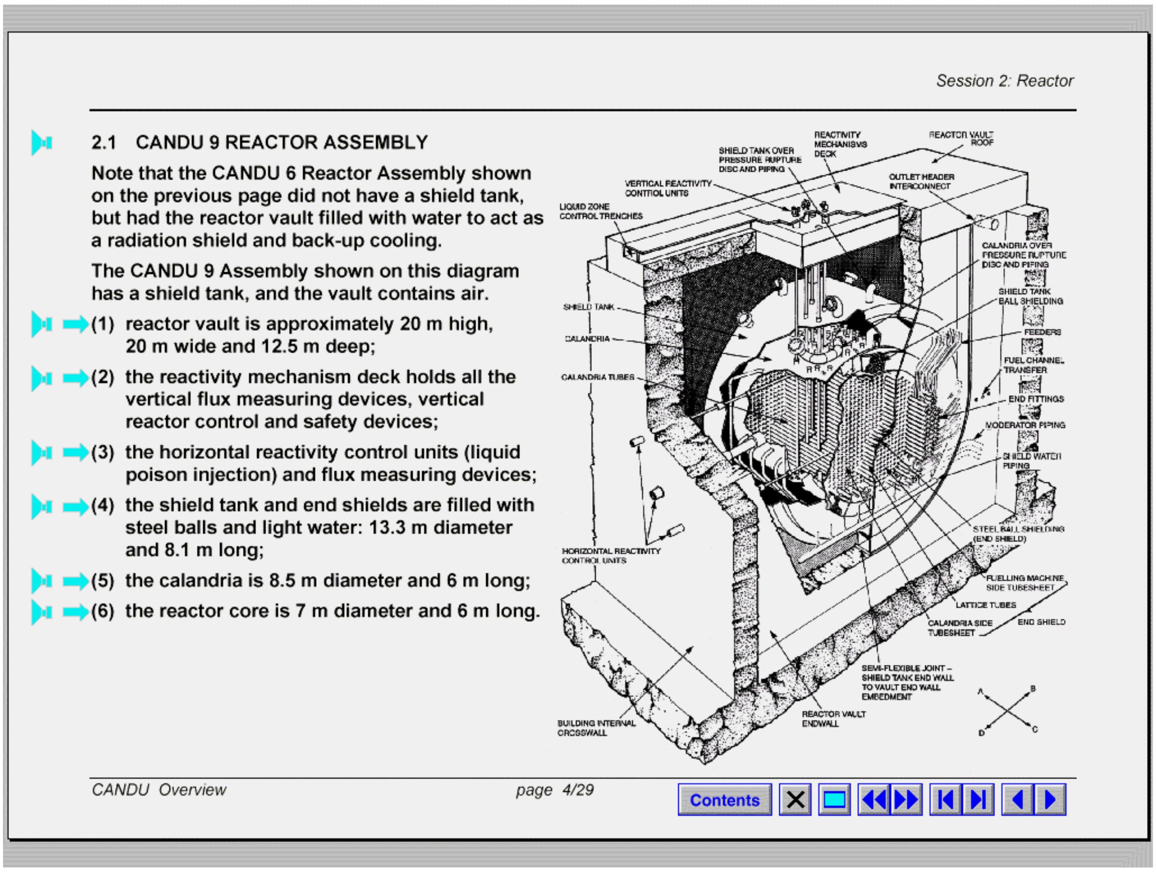
(4) The Shield Tank has a diameter of 13.3 m, and in combination with the End Shields, a length of 8.1 m. The Shield Tank and End Shields completely surround the Calandria, as shown by arrow (a). The space between the Shield Tank shell and the Calandria is filled with ordinary light water. The two End Shields are filled with steel balls and light water, as indicated by arrows (b) and (c). Such shielding allows maintainers to work in the reactor vault and in the fuelling machine vault when the reactor is in the shutdown state. The water in the End Shields is cooled to remove the heat transferred from the heat transport system and generated by neutron absorption.

Arrow (d) points out the three main components that form the structure of the End Shields: the Calandria Side Tubesheet, the Lattice Tubes, and the Fuelling Machine Side Tubesheet.

Arrow (e) indicates the position of one of the Shield Tank over-pressure rupture disc and piping assemblies.

(5) The Calandria contains the Moderator heavy water, and also forms the inner shell of the Shield Tank. It has a diameter of 8.5 m and is 6 m long.

(6) The Reactor Core is regarded as the volume that contains the fuel, which in the case of CANDU corresponds essentially to the volume defined by the pressure tubes inside the Calandria. This volume is approximately 7 m in diameter and 6 m in length. Note that the diameter of the core is 1.5 m less than that of the Calandria, the volume of heavy water between the core and the Calandria wall acts as a reflector of thermal neutrons.



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2.1 CANDU 9 REACTOR ASSEMBLY

Note that the CANDU 6 Reactor Assembly shown on the previous page did not have a shield tank, but had the reactor vault filled with water to act as a radiation shield and back-up cooling.

The CANDU 9 Assembly shown on this diagram has a shield tank, and the vault contains air.

(1) reactor vault is approximately 20 m high, 20 m wide and 12.5 m deep;

(2) the reactivity mechanism deck holds all the vertical flux measuring devices, vertical reactor control and safety devices;

(3) the horizontal reactivity control units (liquid poison injection) and flux measuring devices;

(4) the shield tank and end shields are filled with steel balls and light water: 13.3 m diameter and 8.1 m long;

(5) the calandria is 8.5 m diameter and 6 m long;

(6) the reactor core is 7 m diameter and 6 m long.

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2.2 CALANDRIA AND FUEL CHANNEL ASSEMBLIES

This diagram shows a cross section of the Calandria, End Shield and Fuel Channel assemblies. Many of the components shown on the previous page can be seen more clearly on this figure. The inset shows additional details of a Pressure Tube containing the fuel bundles.

(1) The Calandria Shell and the two End Shields form the Calandria vessel. Note that the diameter of the Calandria shell is stepped down to the smaller diameter of the End Shields, this is done to allow for thermal flexing of the Calandria shell and also to optimize the volume of heavy water for the purpose of neutron reflection.

Each of the two End Shields consists of an inner (or calandria side) and an outer (or fuelling machine side) tubesheet, which are joined by lattice tubes and a peripheral shell to form a closed vessel that is filled with carbon steel balls and shield cooling water.

(2) There is an End Fitting, at arrows (a) at each end of every fuel channel. The End Fitting has a number of purposes, as indicated on the diagram. One of these is to provide the connection between the Pressure Tube and the Reactor Inlet or Outlet Header of the Heat Transport System. This is done via the Feeder Pipe as indicated by Arrow (b).

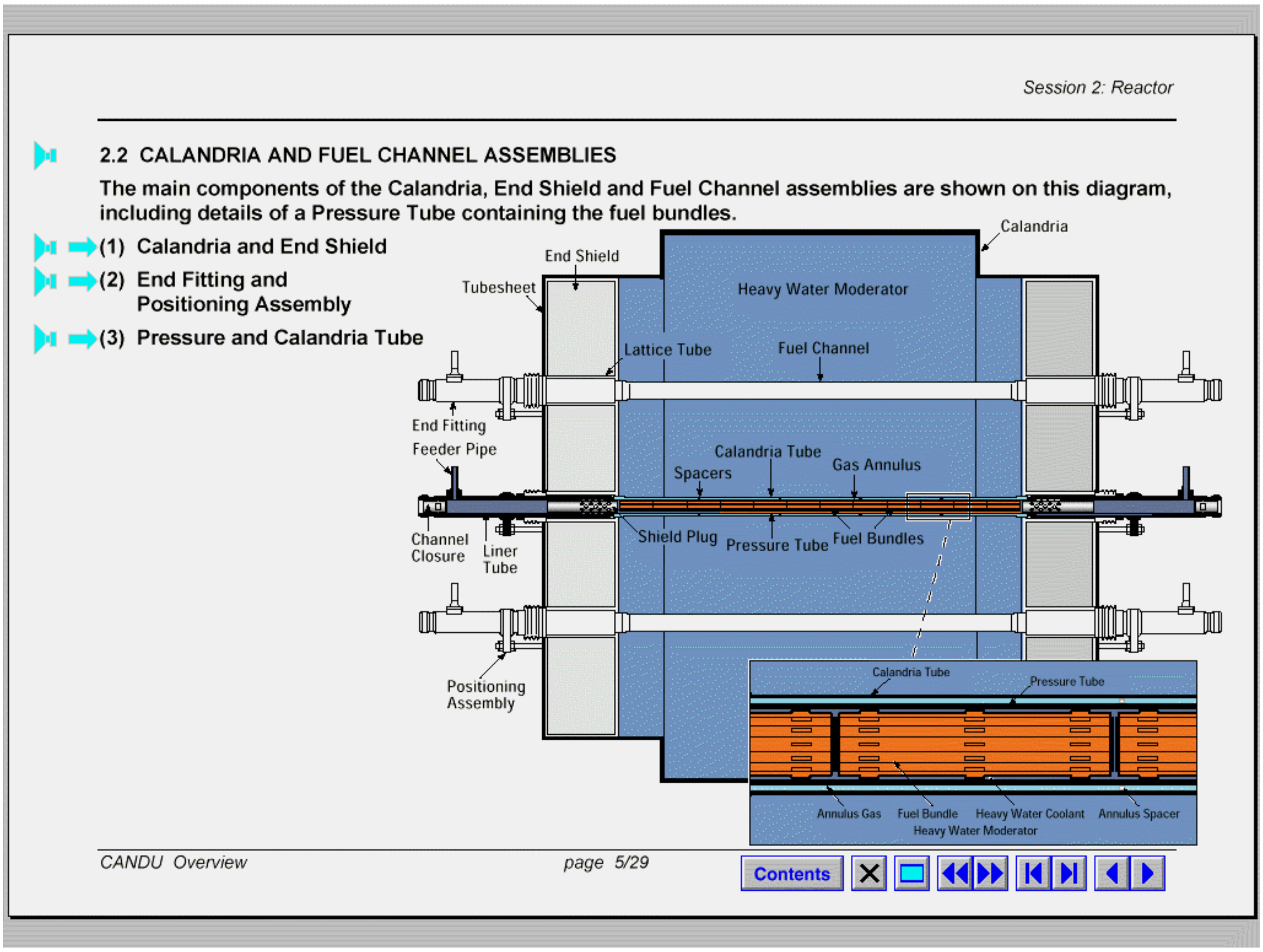
A second function is to allow on-power refuelling, whereby the fuelling machine removes the Channel Closure Plug, shown at arrow (c).

There is a Liner Tube, at arrow (d), that extends through the End Fitting to assist the movement of fuel bundles and the flow of coolant in and out of the Pressure Tube.

A Shield Plug, at arrow (e), is located inside the Liner Tube of the End Fitting, to provide radiation shielding where the End Fitting passes through the Reactor End Shield. It also holds the fuel bundles in the core against the flow of coolant.

A Positioning Assembly, at arrow (f) is attached to each End Fitting to hold the entire fuel channel assembly in place. One end is locked in place while the other allows for pressure tube elongation that takes place under the normal operating conditions of neutron flux and coolant temperature.

(3) The portion of the Fuel Channel that is within the Calandria consists of the Pressure Tube and the Calandria Tube. The Pressure Tubes hold the fuel in the reactor core and allow the pressurized Heat Transport coolant to flow through them and to remove the heat generated in the fuel. As indicated on both the main diagram and the inset, the Pressure Tube is surrounded by the Calandria Tube, and the annular space between them is maintained by spacers and is filled with a gas.



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2.2 CALANDRIA AND FUEL CHANNEL ASSEMBLIES

The main components of the Calandria, End Shield and Fuel Channel assemblies are shown on this diagram, including details of a Pressure Tube containing the fuel bundles.

(1) Calandria and End Shield

(2) End Fitting and Positioning Assembly

(3) Pressure and Calandria Tube

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3. MAIN FEATURES OF THE FUEL BUNDLE

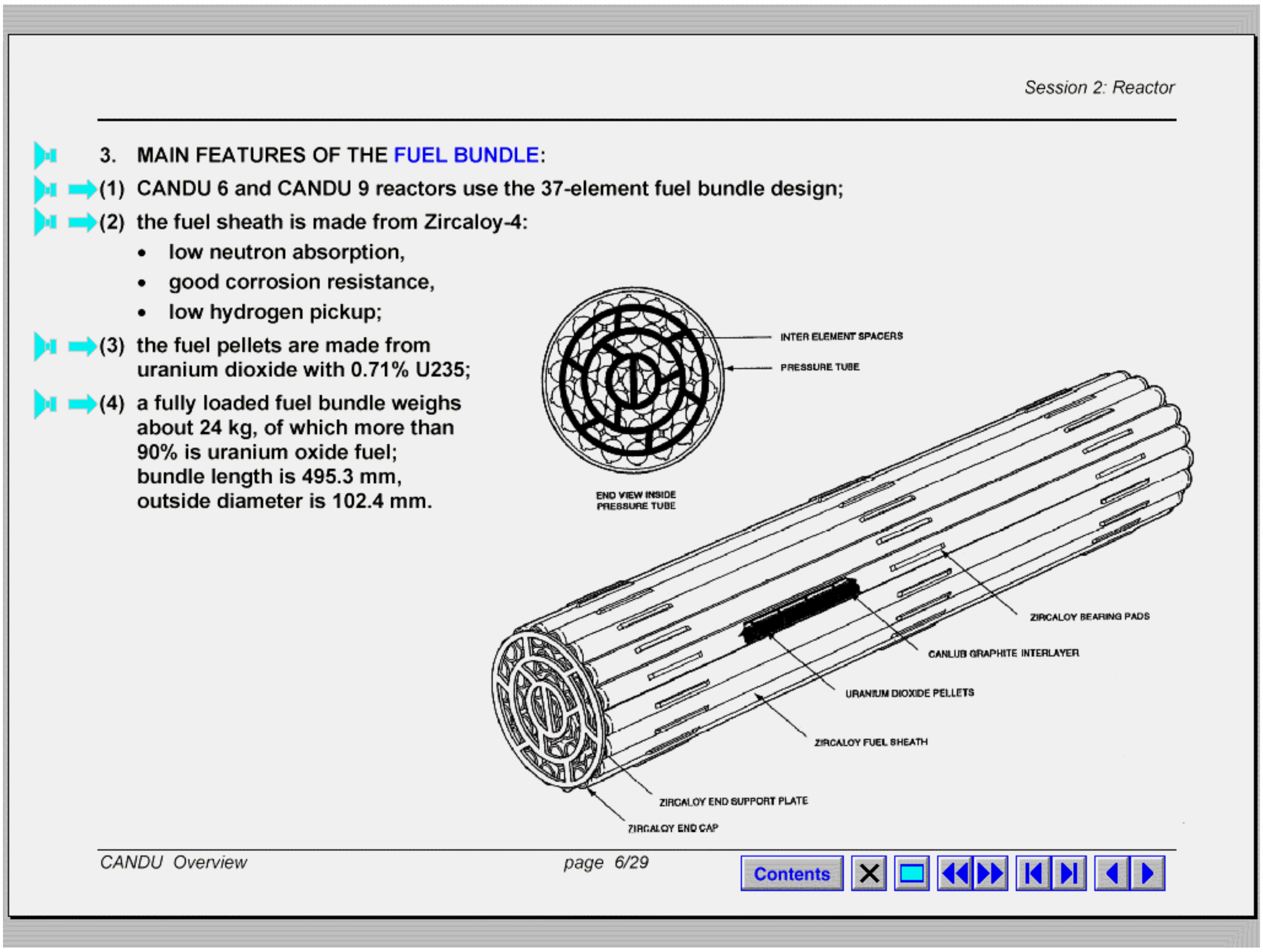
Please point your mouse to the words FUEL BUNDLE in blue letters to see a photograph of fuel bundles being inspected. Since each bundle weighs about 25 kilograms they can be easily handled by one person. The use of natural uranium eliminates the possibility of the fuel going critical in either air or light water.

1. CANDU 6 and CANDU 9 reactors use fuel bundles made up of 37 fuel pencils or elements. Each fuel pencil consists of a Sheath and End Cap that form the so called fuel cladding, made of Zircalloy-4 and enclosing the UO_2 fuel pellets. The Fuel Bundle holds together the 37 fuel elements by two End Plates. The elements are spaced from each other by the End Plates and by Inter Element Spacers at the middle of the bundle. Bearing Pads on the outer pencils support the bundle in the fuel channel.

2. All the structural components, such as the Fuel Sheath, the End Caps, the End Plates, the Inter Element Spacers and the Bearing Pads are made from Zircaloy-4, because it has the desired characteristics of low neutron absorption, low hydrogen pickup and good corrosion resistance.

3. The fuel is made of natural uranium dioxide with 0.71% U235 content, and is formed into high density pellets. There are typically 30 fuel pellets in a fuel pencil. A thin graphite layer, called Canlub is applied on the inner surface of the fuel sheath to reduce the effects of interactions between the pellets and the cladding that would result from changes in reactor power level.

4. Other than the End Plates and the Inter Element Spacers, no other structural components are required for a fuel bundle, since they are supported by the Pressure Tube and held in place by the Shield Plugs. Because the fuel elements are in a horizontal position, gravitational pellet relocation cannot take place. A fully loaded fuel bundle weighs about 24 kilograms, of which more than 90% is uranium oxide fuel.



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3. MAIN FEATURES OF THE FUEL BUNDLE:

(1) CANDU 6 and CANDU 9 reactors use the 37-element fuel bundle design;

(2) the fuel sheath is made from Zircaloy-4:

- low neutron absorption,
- good corrosion resistance,
- low hydrogen pickup;

(3) the fuel pellets are made from uranium dioxide with 0.71% U235;

(4) a fully loaded fuel bundle weighs about 24 kg, of which more than 90% is uranium oxide fuel; bundle length is 495.3 mm, outside diameter is 102.4 mm.

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4. REACTIVITY CONTROL DEVICES

The next few displays present the devices used to control the reactivity of a CANDU core. These devices or mechanisms are used for both regulation (i.e. control) and protection (i.e. safety).

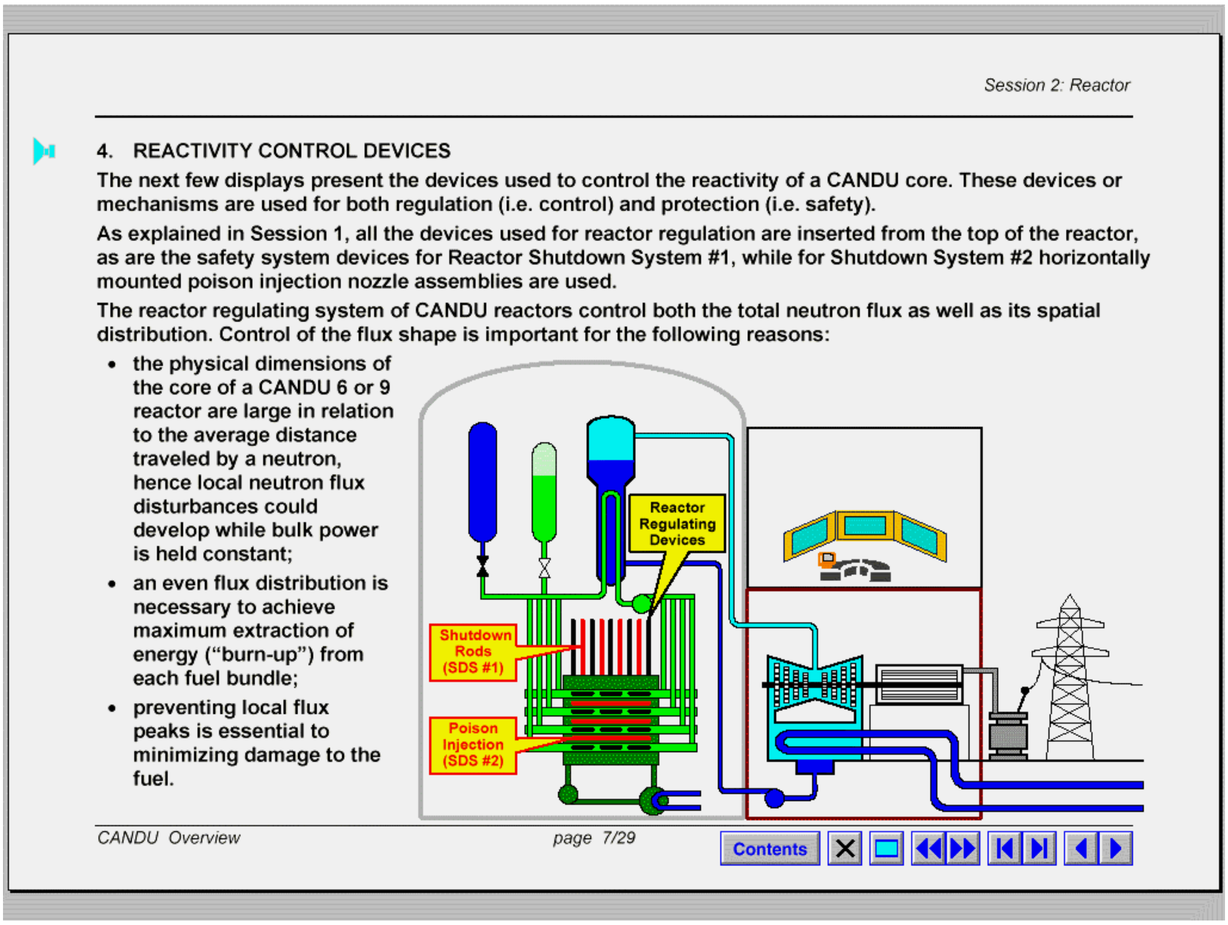
As explained in Session 1, all the devices used for reactor regulation are inserted from the top of the reactor, as are the safety system devices for Reactor Shutdown System #1, while for Shutdown System #2, horizontally mounted poison injection nozzle assemblies are used.

The reactor regulating system of CANDU reactors control both the total neutron flux as well as its spatial distribution. Control of the flux shape is important for the following reasons:

- the physical dimensions of the core of a CANDU 6 or 9 reactor are large in relation to the average distance traveled by a neutron, hence local neutron flux disturbances could develop while bulk power is held constant;

- an even flux distribution is necessary to achieve maximum extraction of energy ("burn-up") from each fuel bundle;

- preventing local flux peaks is essential to minimizing damage to the fuel.



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4.1 LIQUID ZONES

In order to control the spatial flux distribution in the reactor, the core is divided into 14 regions or zones. These zones can be thought of as lightly coupled regions of the core, which means that there is a high probability that a neutron born in the centre of one of these zones will cause fission in the same zone.

In order to control the flux in each zone, two requirements must be met: first the flux has to be measured in each zone, and second, there must be a means of controlling the reactivity in each zone, independently of every other zone.

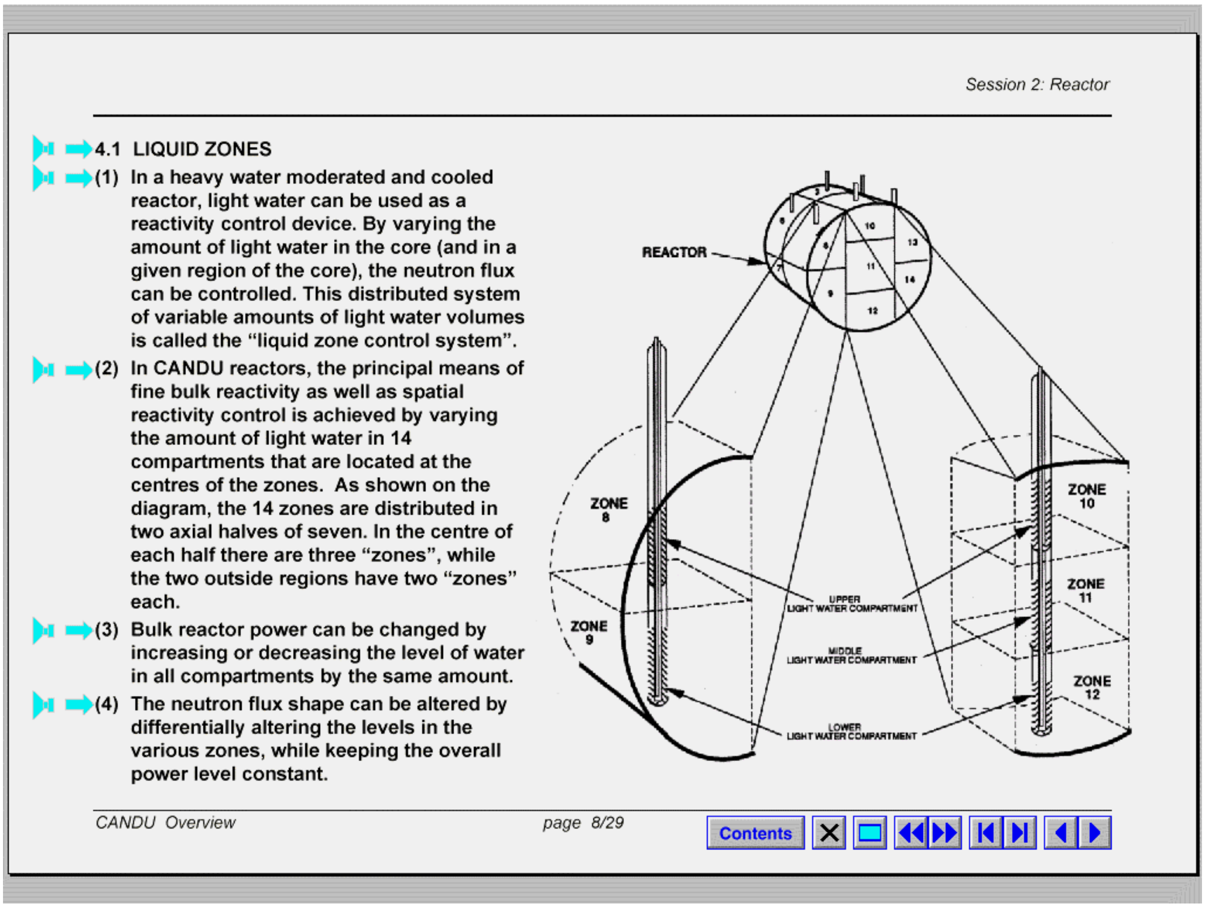
(1). Heavy water moderated reactors such as CANDU rely on a very high level of purity (better than 99%) of D2O. Even a small amount of H2O present in the moderator or the heat transport coolant will absorb a significant number of neutrons, and causing a reduction in fuel conversion efficiency. The fact that light water acts as a strong neutron absorber in a heavy water moderated reactor can be used to devise an effective reactivity control mechanism. Control rods made of neutron absorbing material will distort the flux throughout their range of travel. However, having a light water compartment in a given location of the core, by varying the level of the water in these compartments, the local flux can be altered, without affecting the flux in other parts of the core.

Such a system of compartments containing variable amounts of light water distributed in a CANDU reactor core is called the "liquid zone control system". On the diagram five of the 14 zones are shown enlarged, with the arrows indicating that the level of water in each compartment is variable. As we will see, the level change is achieved by altering the flow differential in and out of each compartment. The small amounts of water flow do not disturb the flux, relative to the effects of the volumes that accumulate in each zone compartment.

(2) The 14 zones are distributed as two axial halves, each half having seven zones. In the illustration the “front” half has zones 8 to 14, and the “back” half zones 1 to 7. The configuration of the zones can also be thought of as seven axial pairs, these being 1 & 13, 2 & 14, 3 & 10, 4 & 11, 5 & 12, 6 & 8, 7 & 9. As illustrated, there are three compartments in each of the two zone controller units that traverse the central zones, namely 3, 4, 5 and 10, 11, 12 respectively, and two compartments in each of the four zone controller units that traverse the outer zones, these being 1 & 2, 6 & 7, 8 & 9, 13 & 14.

(3) The Reactor Regulating System controls the level of water in each compartment. If all the zone levels increase, there will be a negative reactivity change, and the neutron flux will decrease. Increasing or decreasing the level of water in all the compartments by the same amount changes the total or bulk reactor power. Note on the diagram that all the zones have the same level, indicating a uniform flux distribution.

(4) The Reactor Regulating System can also change the water level in each zone compartment by different amounts. In this way the neutron flux shape can be altered to different values in the various zones, while keeping the overall power level constant. In the diagram, I am illustrating a side to side as well as a back to front flux tilt and the corresponding differences in zone levels.



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4.1 LIQUID ZONES

(1) In a heavy water moderated and cooled reactor, light water can be used as a reactivity control device. By varying the amount of light water in the core (and in a given region of the core), the neutron flux can be controlled. This distributed system of variable amounts of light water volumes is called the “liquid zone control system”.

(2) In CANDU reactors, the principal means of fine bulk reactivity as well as spatial reactivity control is achieved by varying the amount of light water in 14 compartments that are located at the centres of the zones. As shown on the diagram, the 14 zones are distributed in two axial halves of seven. In the centre of each half there are three “zones”, while the two outside regions have two “zones” each.

(3) Bulk reactor power can be changed by increasing or decreasing the level of water in all compartments by the same amount.

(4) The neutron flux shape can be altered by differentially altering the levels in the various zones, while keeping the overall power level constant.

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4.2 LIQUID ZONE LEVEL CONTROL SYSTEM

The area of each cylindrical light water zone compartment is fixed, so the volume of water, and hence its reactivity worth can be varied by controlling the level of the water in each compartment. Since the purpose of level control is to control the flux, both neutron flux and zone compartment water level need to be measured in order to ensure that the control system is behaving as intended. In this section we look at a somewhat simplified system of a liquid zone controller.

(1) Near the centre of each zone there is a flux detector that measures the local flux, as shown by arrow (a). The output of the flux detector is read by the Digital Control Computer (DCC), as indicated by arrow (b). After some processing in the DCC, this signal is compared with the flux setpoint that is also calculated by the Reactor Regulating System (RRS) in the DCC. On each iteration of RRS the program computes a control signal based on the error between the setpoint and the flux measurement.

In case of a Reactor Trip the computer generates a control signal to fill zones at a rate of 0.5%FP/sec, while on a Reactor Setback the control signal is for a 0.15%FP/sec fill rate.

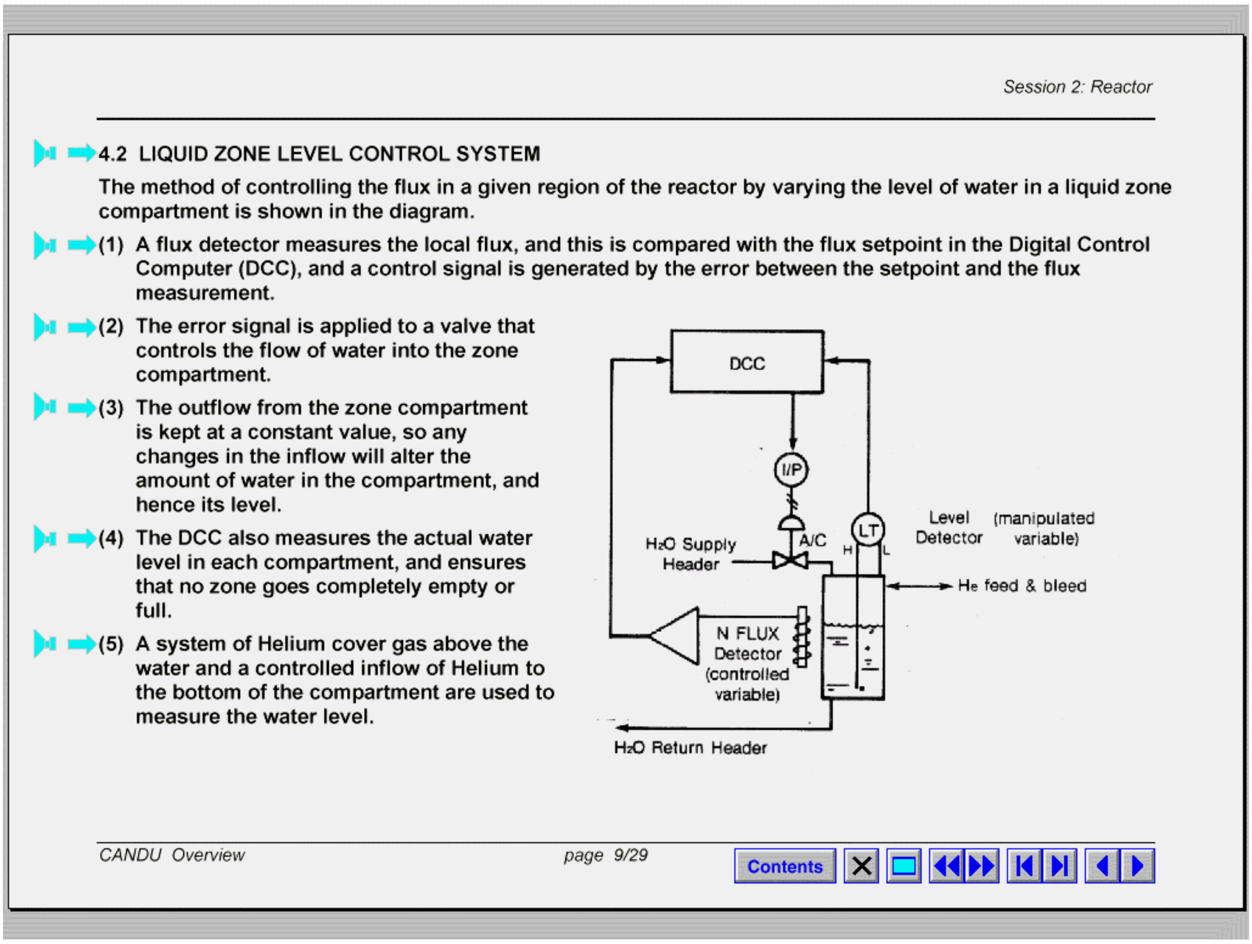
The control signal output from the DCC is at arrow (c), and is applied to a current to air pressure transducer.

(2) The control signal, in the form of air pressure, is applied to a valve that varies the flow of water into the zone compartment. The valve is of the “air to close” type, as indicated by the A/C symbol.

(3) The outflow from the zone compartment is kept at a constant value, so any changes in the inflow will alter the amount of water in the compartment, and hence its level. The constant outflow is achieved by keeping the Helium pressure above the water surface at a constant value, by a system of Helium feed and bleed, that is adding or removing Helium as needed to keep the gas pressure in the compartment at a constant value.

(4) The DCC also measures the actual water level in each compartment, and ensures that no zone goes completely empty or full.

(5) A system of Helium cover gas above the water and a controlled inflow of Helium to the bottom of the compartment are used to measure the water level.



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4.2 LIQUID ZONE LEVEL CONTROL SYSTEM

The method of controlling the flux in a given region of the reactor by varying the level of water in a liquid zone compartment is shown in the diagram.

(1) A flux detector measures the local flux, and this is compared with the flux setpoint in the Digital Control Computer (DCC), and a control signal is generated by the error between the setpoint and the flux measurement.

(2) The error signal is applied to a valve that controls the flow of water into the zone compartment.

(3) The outflow from the zone compartment is kept at a constant value, so any changes in the inflow will alter the amount of water in the compartment, and hence its level.

(4) The DCC also measures the actual water level in each compartment, and ensures that no zone goes completely empty or full.

(5) A system of Helium cover gas above the water and a controlled inflow of Helium to the bottom of the compartment are used to measure the water level.

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4.3 ADJUSTER RODS

The liquid zones, as described in the previous three sections, are the principal means of fine bulk reactivity as well as spatial flux control. However, the limited range of reactivity change between empty and full for all the zones, and the differential reactivity changes that can be realized by the relative levels between zones require other, more coarse methods of reactivity control. Solid neutron absorbers in the form of control rods are used to provide reactivity control beyond the capabilities of the liquid zone system. In CANDU reactors, these control rods are called either Adjusters or Mechanical Control Absorbers, depending on their function and design. In this section we look at Adjuster Rods, and in the next section I will briefly describe the Mechanical Control Absorbers.

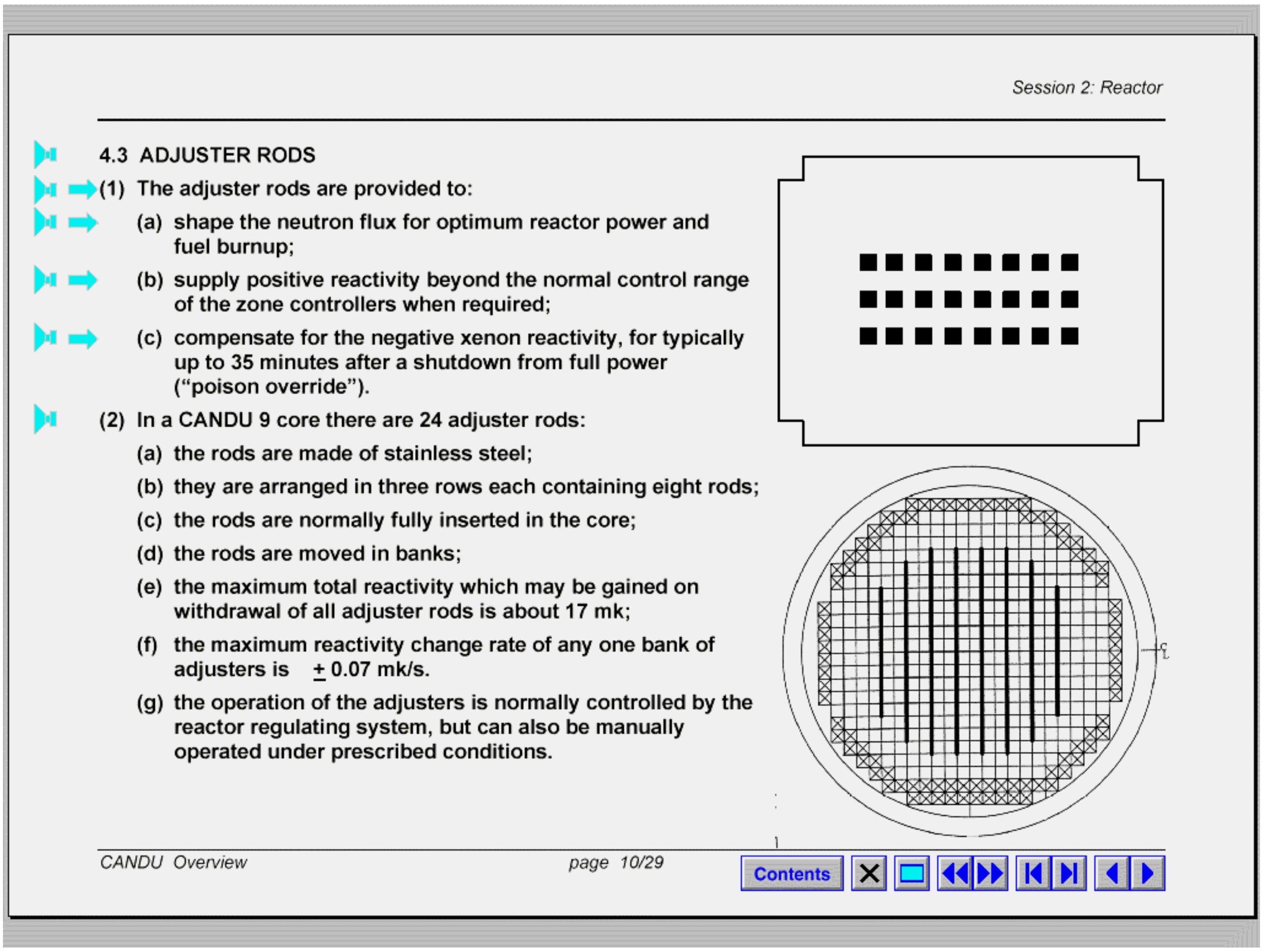
(1) In CANDU reactors, there are three rows of Adjuster Rods as shown in the upper diagram. All three rows have the same arrangement, with the rods being located symmetrically relative to the centre line of the reactor. The rods near the outer parts of the core are shorter than the ones closer to the middle, to follow the circular shape of the core. In CANDU 6 reactors there are 21 Adjuster Rods, and for CANDU 9 reactors 24 Adjusters are used. The Adjuster Rods have the following three purposes:

  (a) As shown in the diagram, the neutron flux without the Adjuster Rods would have a cosine shape. A reactor with this neutron flux and power distribution would only be able to produce maximum power from the bundles near the centre of the core, all the other bundles would be producing less and less power as their position moved away from the centre.

  To achieve maximum reactor power and fuel burnup, as many as possible of the fuel bundles should be producing power at their rated value. This requires flatting, or “adjusting” the flux, as shown in the diagram, with the use of the Adjuster Rods. Hence the name for these control rods. Of course there is a penalty in terms of fuel burn-up, as the Adjuster Rods absorb some of the neutrons that could otherwise cause fission.

  (b) The liquid zone controllers, as described previously, have a limited range of reactivity control. If there is a need to supply positive reactivity beyond the normal control range of the zone controllers, typically in the case when the zone controller water levels have been reduced as much as possible, withdrawal of Adjuster Rods can provide additional positive reactivity. Such situations may arise during fast power increases, or if there has been a delay in refuelling the reactor.

  (c) If reactor power is reduced significantly after prolonged, at least several days of operation at a given, usually 100% full power level, Xenon poison will build up in the core. By withdrawing the Adjuster Rods, the negative reactivity effect of Xenon can be compensated up to the reactivity worth of the Adjuster Rods. In case of a fast reactor shutdown such as a reactor trip from 100% full power, the complete withdrawal of all the Adjuster Rods will be able to compensate for the Xenon poison for typically 35 minutes. This is called the “poison override” time.



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4.3 ADJUSTER RODS

(1) The adjuster rods are provided to:

  (a) shape the neutron flux for optimum reactor power and fuel burnup;

  (b) supply positive reactivity beyond the normal control range of the zone controllers when required;

  (c) compensate for the negative xenon reactivity, for typically up to 35 minutes after a shutdown from full power (“poison override”).

(2) In a CANDU 9 core there are 24 adjuster rods:

  (a) the rods are made of stainless steel;

  (b) they are arranged in three rows each containing eight rods;

  (c) the rods are normally fully inserted in the core;

  (d) the rods are moved in banks;

  (e) the maximum total reactivity which may be gained on withdrawal of all adjuster rods is about 17 mk;

  (f) the maximum reactivity change rate of any one bank of adjusters is ± 0.07 mk/s.

  (g) the operation of the adjusters is normally controlled by the reactor regulating system, but can also be manually operated under prescribed conditions.

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(2) In a CANDU 9 core there are 24 adjuster rods, made of stainless steel.

The rods are arranged in three rows across the radial direction of the core, with each row containing eight rods. The rods are normally fully inserted in the core to shape the flux and to be a source of positive reactivity.

The Adjuster Rods, as all reactivity control mechanisms, are normally moved by the Reactor Regulating System to control bulk reactor power. When such movements take place, they involve a pre-designated group of rods, since the movement of a single rod would not normally provide a sufficient rate of reactivity change. Each such group of rods is called a “bank”. There are eight banks of Adjuster Rods in a CANDU 9 reactor. The banks are designed to have approximately equal reactivity values, so banks containing rods in high flux regions will have two rods, intermediate flux regions will have three, and low flux regions four Adjuster Rods in the bank. The rods in a bank are chosen so that their withdrawal will not cause excessive flux distortions, and the banks are designed to be withdrawn in a sequence that also minimizes distortion of the spatial flux. Conversely, since as the Adjusters are withdrawn the flux will tend to assume the cosine shape, the maximum power that the reactor can produce is limited by the number of Adjuster Rods that are not fully inserted, that is partially or fully withdrawn, from the core.

The maximum total reactivity that may be gained on withdrawal of all adjuster rods is in the order of 16 - 18 mk, and the maximum reactivity change rate of any one bank of adjusters is ± 0.07 mk/second.

As I mentioned earlier, the operation of the adjusters is normally controlled by the reactor regulating system, but they can also be operated manually under prescribed conditions.

4.4 MECHANICAL CONTROL ABSORBERS

As described in the previous two sections, the liquid zones have limited range of reactivity control, and solid neutron absorbers in the form of control rods are used to provide reactivity control beyond the capabilities of the liquid zone system. In CANDU reactors, these control rods are called either Adjusters or Mechanical Control Absorbers, depending on their function and design. In Section 5 we looked at the Adjuster Rods, which can provide additional positive reactivity by withdrawal from the core. In this section I will briefly describe how additional negative reactivity can be realized by inserting the Mechanical Control Absorber Rods into the core.

(1) In CANDU 6 and 9 reactors there are four mechanical control absorber rods or MCAs, as shown in the diagram. They consist of tubes of cadmium sandwiched between stainless steel tubes.

(2) The normal position of the Control Absorbers is out of the core, i.e. they are “poised” for insertion when needed. Such need typically arises during power level changes, particularly during large power level reductions, in part due to the temperature effects that result in an inherent reactivity increase on a power level reduction. The MCAs are also designed to realize a rapid step-like reduction in reactor power when required by “Stepback” conditions.

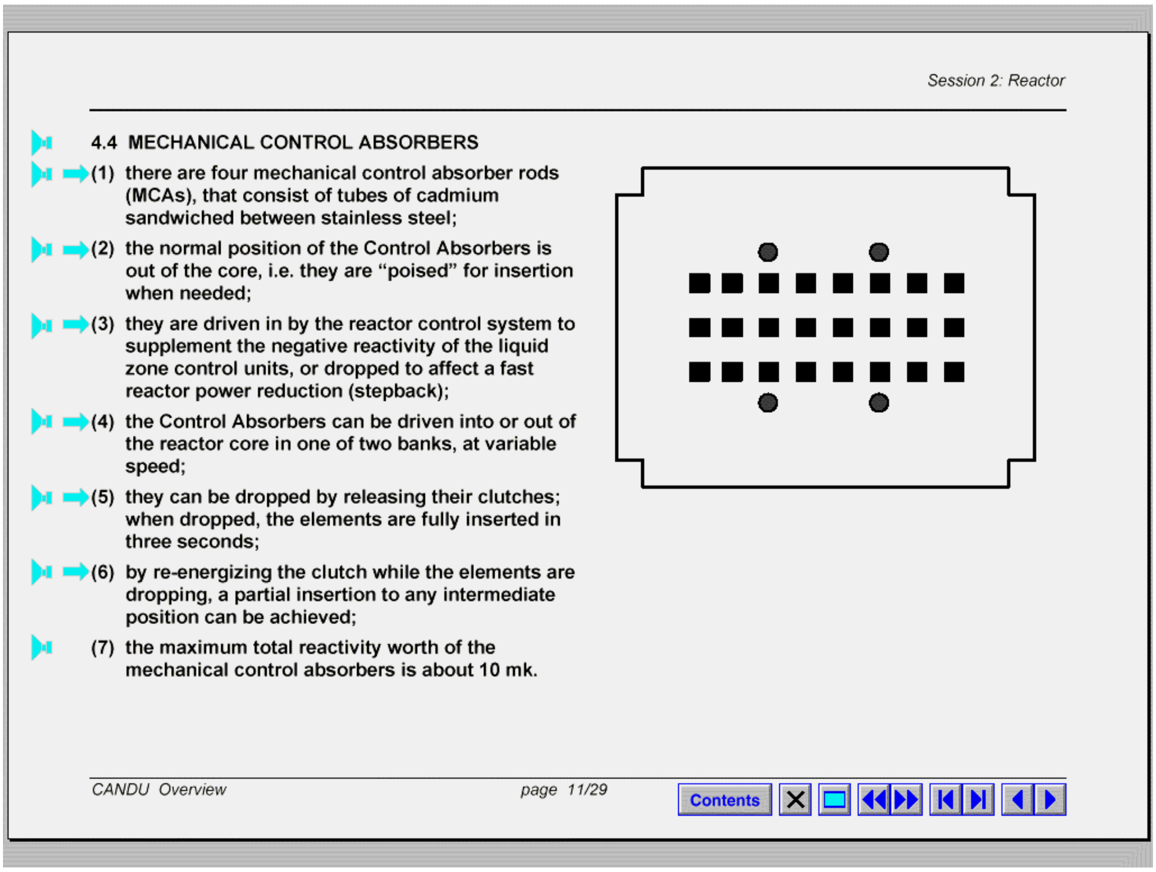
(3) The Mechanical Control Absorbers, as all reactivity control mechanisms, are normally moved by the Reactor Regulating System to control bulk reactor power. They can be driven into the core to supplement the negative reactivity of the liquid zone control units, or dropped partially into the reactor to affect a fast reactor power reduction of typically 40%FP, called a stepback. On a reactor trip the MCAs are fully dropped into the core to assist fast reactor shutdown. It is also possible to operate the Control Absorbers manually under prescribed conditions.

(4) For normal reactivity control purposes the Mechanical Control Absorbers are driven into or out of the reactor core by the Reactor Regulating System in one of two banks. At full speed the rods can cover the full travel distance in 150 seconds. The actual driving speed can be varied by the Reactor Regulating System from 50% to 100% of full speed, depending on the power error.

(5) When required to achieve a sudden reduction of reactor power the MCAs can be dropped by releasing their clutches. When dropped, the elements are fully inserted into the core in three seconds.

(6) If only a partial reduction of reactor power is required, for example a step-like reduction by 40% FP, the clutches can be re-energized while the elements are dropping to achieve a partial insertion to any intermediate position.

(7) The total reactivity worth of the four Mechanical Control Absorbers is about 10 mk.



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4.4 MECHANICAL CONTROL ABSORBERS

(1) there are four mechanical control absorber rods (MCAs), that consist of tubes of cadmium sandwiched between stainless steel;

(2) the normal position of the Control Absorbers is out of the core, i.e. they are “poised” for insertion when needed;

(3) they are driven in by the reactor control system to supplement the negative reactivity of the liquid zone control units, or dropped to affect a fast reactor power reduction (stepback);

(4) the Control Absorbers can be driven into or out of the reactor core in one of two banks, at variable speed;

(5) they can be dropped by releasing their clutches; when dropped, the elements are fully inserted in three seconds;

(6) by re-energizing the clutch while the elements are dropping, a partial insertion to any intermediate position can be achieved;

(7) the maximum total reactivity worth of the mechanical control absorbers is about 10 mk.

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4.5 SHUTDOWN RODS

CANDU 6 and 9 reactors have two fully independent reactor shutdown systems, and these are also independent of the systems and components used for reactor regulation. The Shutdown Rods provide the means of large reactivity insertion for Shutdown System Number One, in short SDS#1, in the form of 32 solid neuron absorbing rods that are dropped into the core on an SDS#1 initiated reactor trip. The arrangement of the 32 rods is shown in top view on the diagram.

(1) The Shutdown Rods are very similar in construction to the Control Absorbers, consisting of tubes of cadmium sandwiched between stainless steel tubes. The normal position of the Shutdown Rods is out of the core, i.e. they are “poised” for insertion when the reactor needs to be rapidly shut down. Shutdown Rods in the out-of-core position are indicated by arrows (a), and in the fully inserted position by arrows (b) on the diagram.

(2) When all 32 Shutdown Rods are in their fully inserted position, their total reactivity worth is between -60 and -70 mk. The reactivity worth of the Shutdown Rods is such that in the case of two of the most effective rods not dropping into the core, the reactor will still be safely shut down for all design basis accidents.

(3) In order to increase the speed of insertion for the Shutdown Rods, a small accelerating force is applied to them in the form of a compressed spring that covers the top 0.6 metres of travel for each rod. With this spring assisted gravity drop, the Shutdown Rods are fully inserted in 2 seconds.

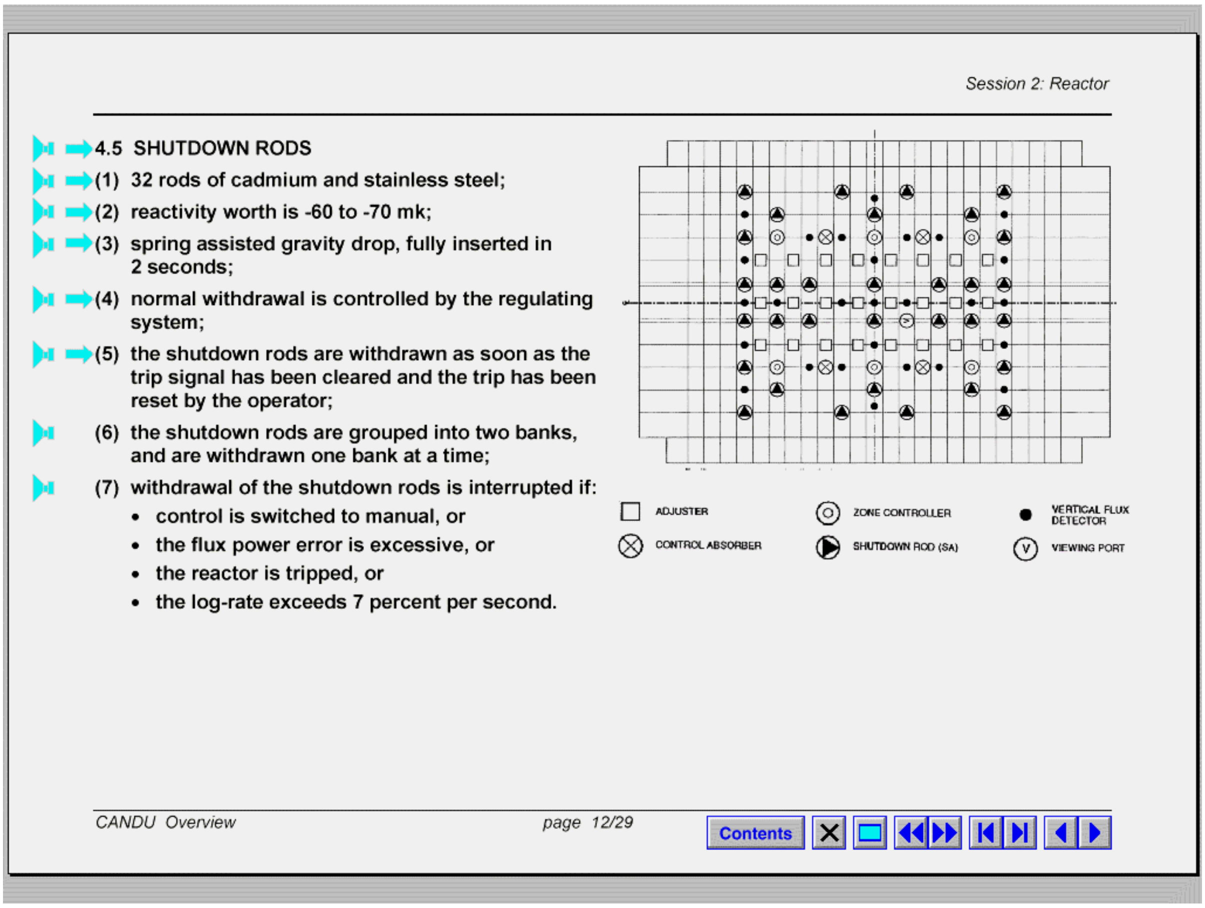
(4) The withdrawal of the Shutdown Rods is controlled by the Reactor Regulating System, by driving the motor that withdraws the Shutdown Rods. However, the clutch between the motor and the shaft that pulls the Rods is part of the Safety System. Until the clutch is energized and closed, the rods cannot be pulled. This design achieves the desired independence between Reactor Shutdown and Regulation.

(5) The Shutdown Rods are withdrawn as soon as the trip signal has been cleared and the trip has been reset by the operator.

(6) The Shutdown Rods are grouped into two banks, and are withdrawn one bank at a time.

(7) Withdrawal of the Shutdown Rods is interrupted if:

- control is switched to manual, or
- the flux power error is excessive, or
- the reactor is tripped, or
- the log-rate exceeds 7 percent per second.



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4.5 SHUTDOWN RODS

(1) 32 rods of cadmium and stainless steel;

(2) reactivity worth is -60 to -70 mk;

(3) spring assisted gravity drop, fully inserted in 2 seconds;

(4) normal withdrawal is controlled by the regulating system;

(5) the shutdown rods are withdrawn as soon as the trip signal has been cleared and the trip has been reset by the operator;

(6) the shutdown rods are grouped into two banks, and are withdrawn one bank at a time;

(7) withdrawal of the shutdown rods is interrupted if:

- **control is switched to manual, or**
- **the flux power error is excessive, or**
- **the reactor is tripped, or**
- **the log-rate exceeds 7 percent per second.**

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4.6 SUMMARY OF REACTIVITY CONTROL DEVICES

All the reactivity devices considered in this Section, for regulation as well as shutdown purposes, are installed from above the Calandria. The drive motors, connections for electrical, water and Helium supplies are all made at the Reactivity Mechanism Deck. Because the solid control rods, including Adjusters, Control Absorbers and Shutdown Rods need to travel from being fully inserted into the core to a position that is completely out of the core, there must be sufficient distance between the top of the Calandria and the bottom of the Reactivity Mechanism Deck to make room for these rods in their out of core positions. All the reactivity devices in CANDU 6 and 9 are neutron absorbers, and they function by having more or less neutron absorbing material in the reactor. Control is provided for the following effects:

(1) Long-term bulk reactivity is mainly controlled by on-power refuelling. This is the only method for adding absolute positive reactivity to the core, instead of only reducing the amount of negative reactivity.

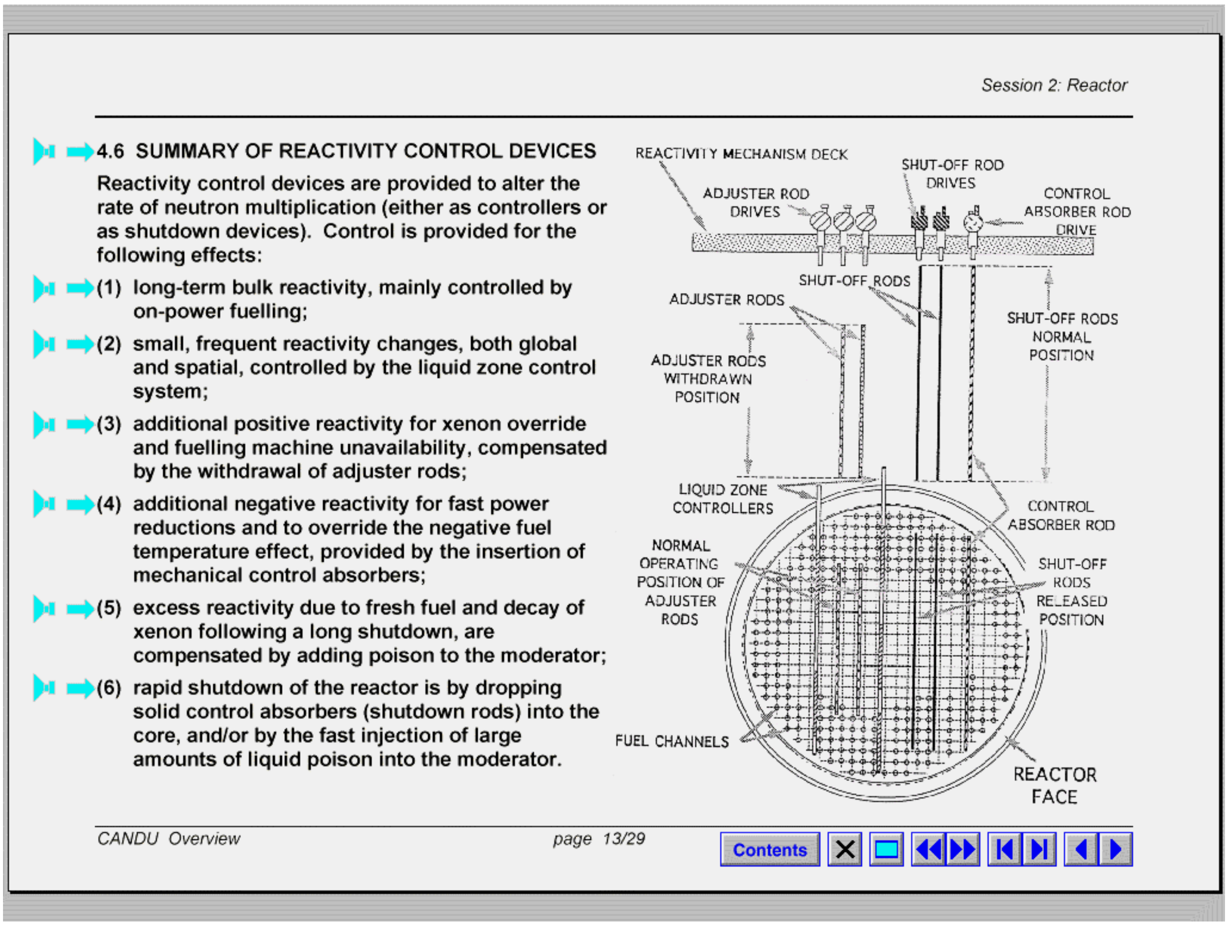
(2) Small, frequent reactivity changes, for both global and spatial neutron power, are controlled by the liquid zone control system.

(3) Positive reactivity for xenon override and fuelling machine unavailability, is provided by withdrawing Adjuster Rods from their normal position in the core shown as (a) to their “parked” position above the Calandria, at position (b).

(4) Negative reactivity to supplement the liquid zones, particularly for fast power reductions and to override the negative fuel temperature effect for large power level decreases, is provided by the insertion of mechanical control absorbers from their normal “poised position” at (a), to part way or all the way to their fully inserted position at (b).

(5) Excess reactivity due to fresh fuel and decay of xenon following a long shutdown, are compensated by adding poison to the moderator.

(6) Rapid shutdown of the reactor is by dropping solid control absorbers (shutdown rods) into the core, from position (a) to position (b), and/or by the fast injection of large amounts of liquid poison into the moderator, as indicated by arrow (c).



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4.6 SUMMARY OF REACTIVITY CONTROL DEVICES

Reactivity control devices are provided to alter the rate of neutron multiplication (either as controllers or as shutdown devices). Control is provided for the following effects:

(1) long-term bulk reactivity, mainly controlled by on-power fuelling;

(2) small, frequent reactivity changes, both global and spatial, controlled by the liquid zone control system;

(3) additional positive reactivity for xenon override and fuelling machine unavailability, compensated by the withdrawal of adjuster rods;

(4) additional negative reactivity for fast power reductions and to override the negative fuel temperature effect, provided by the insertion of mechanical control absorbers;

(5) excess reactivity due to fresh fuel and decay of xenon following a long shutdown, are compensated by adding poison to the moderator;

(6) rapid shutdown of the reactor is by dropping solid control absorbers (shutdown rods) into the core, and/or by the fast injection of large amounts of liquid poison into the moderator.

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5. REACTOR REGULATING SYSTEM (RRS)

The next few pages present the instrumentation and signal processing used by the Reactor Regulating System. Included are the various methods of Neutron Flux and Thermal Power Measurements, and how they are combined to deteremine actual reactor power. The control algorithms are implemented as computer programs that receive the measurement signals, process them, and using the reactor setpoint, compute the demanded power and the power error. The control programs determine which reactivity mechanism is to move, by what amount and at what rate. RRS is designed to perform the following functions:

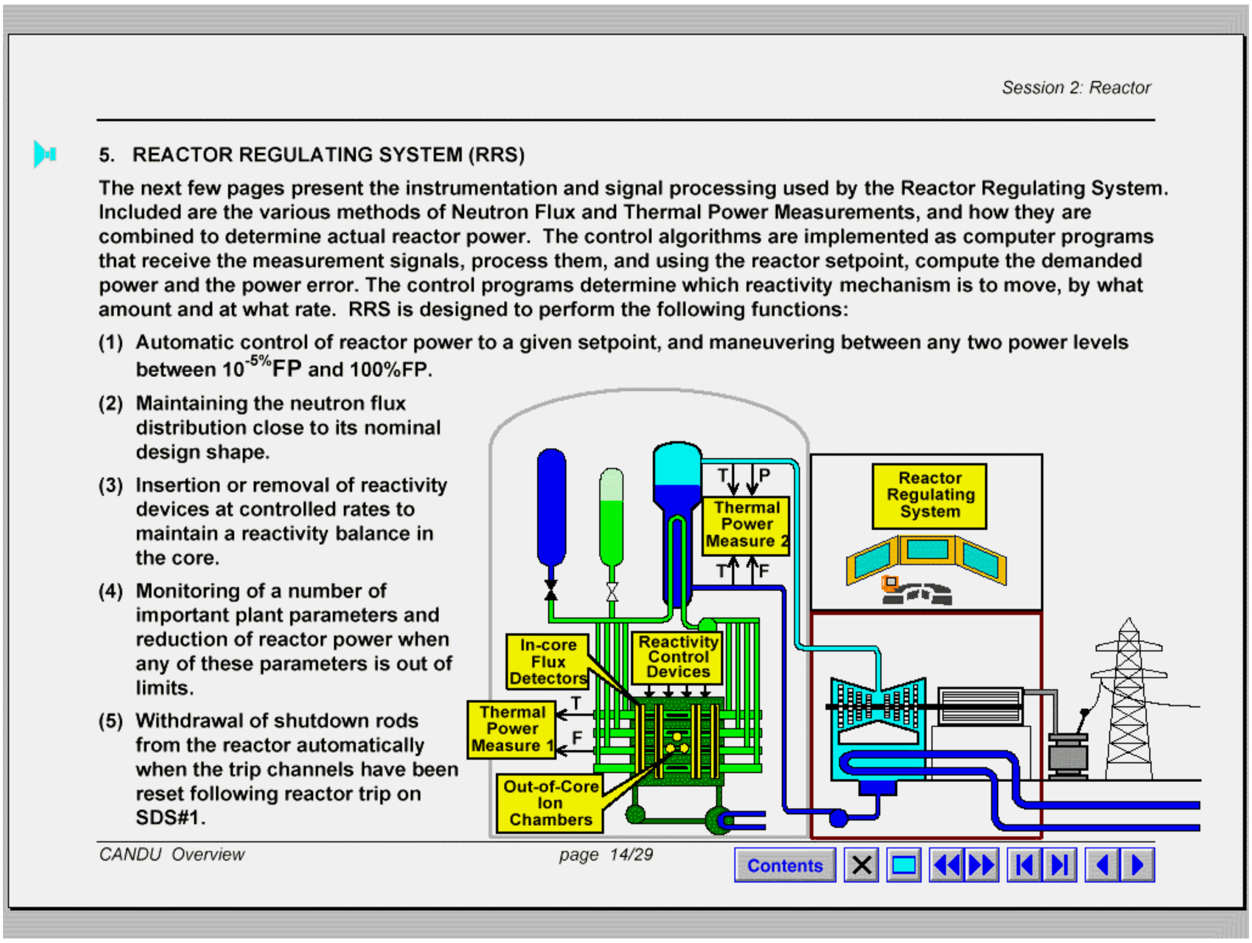
(1) Automatic control of reactor power to a given setpoint, and maneuvering between any two power levels between $10^{-5\%FP}$ and 100%FP.

(2) Maintaining the neutron flux distribution close to its nominal design shape.

(3) Insertion or removal of reactivity devices at controlled rates to maintain a reactivity balance in the core.

(4) Monitoring of a number of important plant parameters and reduction of reactor power when any of these parameters is out of limits.

(5) Withdrawal of shutdown rods from the reactor automatically when the trip channels have been reset following reactor trip on SDS#1.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5. REACTOR REGULATING SYSTEM (RRS)

The next few pages present the instrumentation and signal processing used by the Reactor Regulating System. Included are the various methods of Neutron Flux and Thermal Power Measurements, and how they are combined to determine actual reactor power. The control algorithms are implemented as computer programs that receive the measurement signals, process them, and using the reactor setpoint, compute the demanded power and the power error. The control programs determine which reactivity mechanism is to move, by what amount and at what rate. RRS is designed to perform the following functions:

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(4) Monitoring of a number of important plant parameters and reduction of reactor power when any of these parameters is out of limits.

(5) Withdrawal of shutdown rods from the reactor automatically when the trip channels have been reset following reactor trip on SDS#1.

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5.1 REGULATING SYSTEM ION CHAMBERS

(1) There are three horizontally mounted ion chamber assemblies of the type shown on the previous diagram at the side of the calandria. One ion chamber from each housing supplies a signal for the purpose of reactor regulation that is fed to an amplifier. The amplifier processes the input signal from the ion chamber so as to produce three different output signals. Each of these signals, and remember that that there are three such amplifiers so that each of these signals is in fact triplicated, are used for different purposes:

(a) The range of the Linear N signals is from 0 to 150 %FP, and they are connected to indicating meters on the Main Control Room Panels.

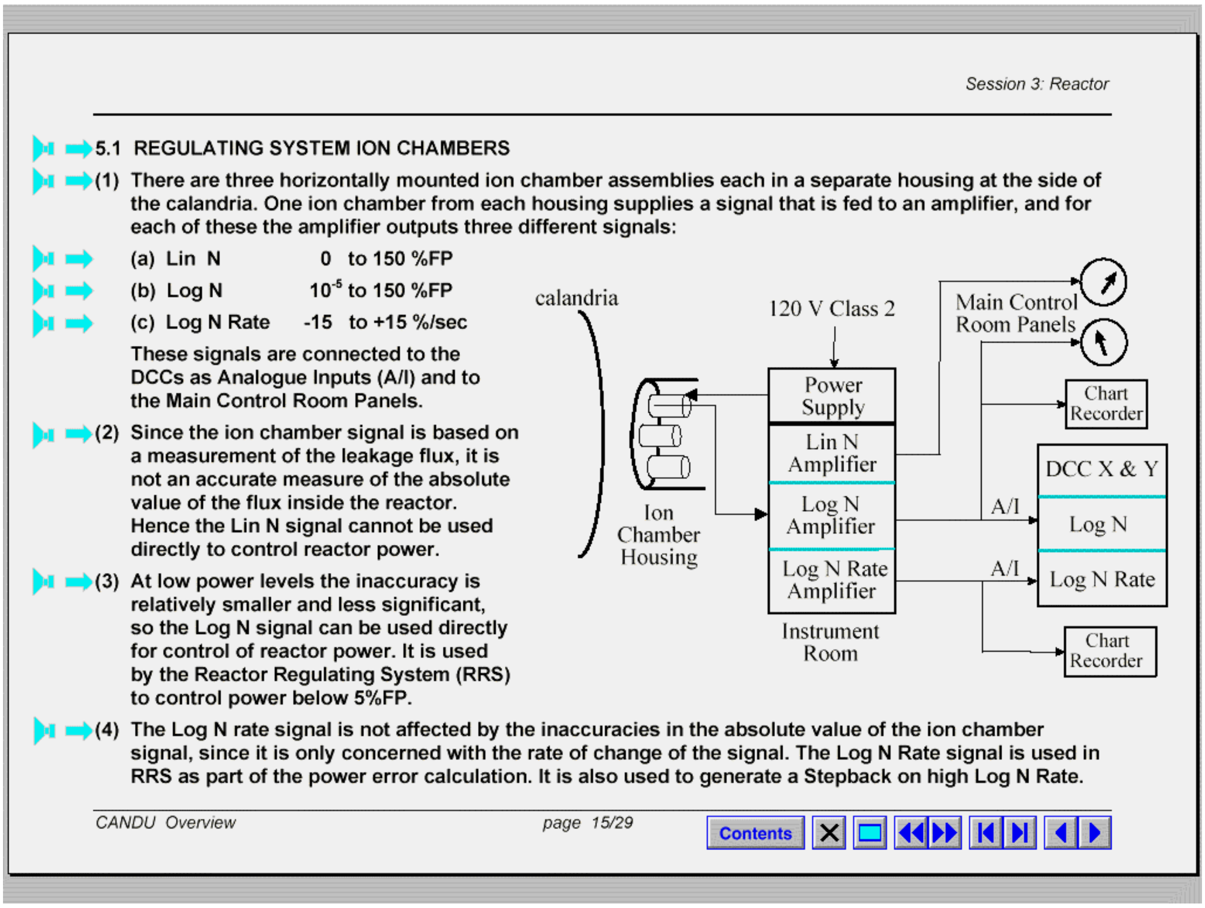
(b) The range of the Log N signals are from 10^{-5} to 150 %FP. These signals are displayed on the Main Control Room Panels, and they are connected as Analogue Inputs shown as A/I, to both digital control computers DCC'X' and DCC'Y'.

(c) The range of the Log N Rate signal are from -15 to +15 %/sec. These signals are displayed in the Main Control Room and are connected as A/Is to both DCCs.

(2) Since the ion chamber signal is based on a measurement of the leakage flux, it is not an accurate measure of the absolute value of the flux inside the reactor. Hence the Lin N signal cannot be used directly to control reactor power, but it is a useful indication to have in the Control Room.

(3) At low power levels the inaccuracy of the ion chamber reading due to local flux distortions is relatively small and not so significant, so at low power levels the Log N signal can be used directly for control of reactor power. It is used by the Reactor Regulating System (RRS) to control power below 15%FP.

(4) The Log N Rate signal is not affected by the inaccuracies in the absolute value of the ion chamber signal, since it is only concerned with the rate of change of the signal. The Log N Rate signal is used in RRS as part of the power error calculation. It is also used to generate a Stepback signal on high Log N Rate.



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5.1 REGULATING SYSTEM ION CHAMBERS

(1) There are three horizontally mounted ion chamber assemblies each in a separate housing at the side of the calandria. One ion chamber from each housing supplies a signal that is fed to an amplifier, and for each of these the amplifier outputs three different signals:

(a) Lin N	0 to 150 %FP	
(b) Log N	10^{-5} to 150 %FP	
(c) Log N Rate	-15 to +15 %/sec	

These signals are connected to the DCCs as Analogue Inputs (A/I) and to the Main Control Room Panels.

(2) Since the ion chamber signal is based on a measurement of the leakage flux, it is not an accurate measure of the absolute value of the flux inside the reactor. Hence the Lin N signal cannot be used directly to control reactor power.

(3) At low power levels the inaccuracy is relatively smaller and less significant, so the Log N signal can be used directly for control of reactor power. It is used by the Reactor Regulating System (RRS) to control power below 5%FP.

(4) The Log N rate signal is not affected by the inaccuracies in the absolute value of the ion chamber signal, since it is only concerned with the rate of change of the signal. The Log N Rate signal is used in RRS as part of the power error calculation. It is also used to generate a Stepback on high Log N Rate.

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5.2 IN-CORE VERTICAL FLUX DETECTORS FOR THE REACTOR REGULATING SYSTEM

For the control of the reactor power in the linear or power generation range, from above 5%FP, CANDUs use the Inconel type in-core flux detectors. These detectors are located in the 14 control zones, so that both the spatial distribution and the total flux of the reactor are measured and controlled. The diagram illustrates a segment of the core, in a region that includes 16 fuel channels, and shows one such in-core flux detector between the row of fuel channels and spanning a distance of approximately three lattice pitches.

There is a distinction between the Vertical In-Core Flux Detectors used for reactor regulation and the Horizontal in-Core Flux Detectors used for the second reactor shutdown system.

(1) In CANDU reactors there are 28 in-core Vertical Flux Detectors (VFDs) using Platinum clad Inconel to measure the neutron flux in each of the 14 reactor zones. Each zone has two detectors to provide redundancy, and as shown on the diagram, the two detectors from the same zone are connected to two different amplifiers.

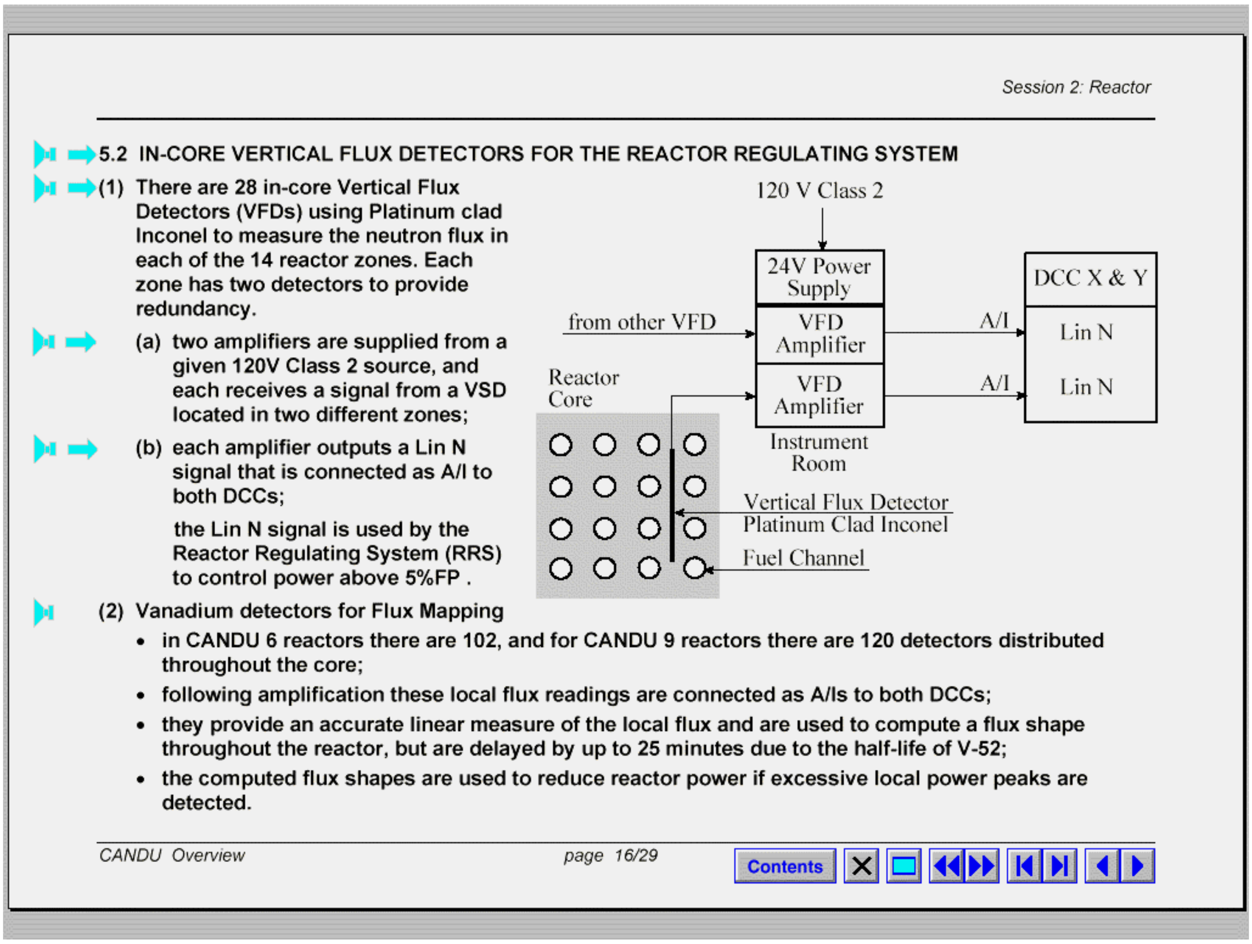
 (a) Although these detectors are "self-powered" as I explained in the previous section, the signals generated by the detectors need to be amplified before they can be connected to the DCCs. The design has two amplifiers supplied from a given 120V Class 2 source, and to ensure redundancy, each of a pair of amplifiers receives its input signal from a VSD located in two different zones, as illustrated.

 (b) Each amplifier outputs a Lin N signal that is connected as A/I to both DCCs. It is this Linear Neutron signal that is used by the Reactor Regulating System (RRS) to control power above 5%FP, both spatially and for the reactor as a whole. However, because of the gamma sensitivities and discussed in the previous section, the flux detector signals cannot be used directly for the control of reactor power, but need some corrections. The bulk power measurement needs to be calibrated by the thermal power measurements, while for the purpose of controlling the spatial power distribution, the calibration uses the output of the Flux Mapping routine.

(2) The Vanadium detectors I described in the previous section are used for the purpose of determining an accurate distribution of the neutron flux in the reactor by the use of a Flux Mapping routine.

In CANDU 6 reactors there are 102, and for CANDU 9 reactors there are 120 Vanadium detectors distributed throughout the core to measure the local flux. Following amplification these local flux readings are connected as A/Is to both DCCs. The computers use these signal as input to a mathematical representation of the flux shapes, and the programs output estimates of the flux distribution every 2 minutes. These estimates are accurate linear measures of the flux shape throughout the reactor, but due to the 5.5 minute half-life of V-52 the desired accuracy is not reached for about 25 minutes following a change of neutron flux.

The output of the Flux Mapping Routine is used to calibrate the Inconel flux detector readings for the purpose of fine tuning the zonal power measurement and control, as well as to reduce reactor power if excessive local power peaks are detected.



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5.2 IN-CORE VERTICAL FLUX DETECTORS FOR THE REACTOR REGULATING SYSTEM

(1) There are 28 in-core Vertical Flux Detectors (VFDs) using Platinum clad Inconel to measure the neutron flux in each of the 14 reactor zones. Each zone has two detectors to provide redundancy.

(a) two amplifiers are supplied from a given 120V Class 2 source, and each receives a signal from a VSD located in two different zones;

(b) each amplifier outputs a Lin N signal that is connected as A/I to both DCCs;

the Lin N signal is used by the Reactor Regulating System (RRS) to control power above 5%FP .

(2) Vanadium detectors for Flux Mapping

- **in CANDU 6 reactors there are 102, and for CANDU 9 reactors there are 120 detectors distributed throughout the core;**
- **following amplification these local flux readings are connected as A/Is to both DCCs;**
- **they provide an accurate linear measure of the local flux and are used to compute a flux shape throughout the reactor, but are delayed by up to 25 minutes due to the half-life of V-52;**
- **the computed flux shapes are used to reduce reactor power if excessive local power peaks are detected.**

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5.3 THERMAL POWER MEASUREMENT

So far in this Section we have been dealing with the methods used for measuring the neutron flux. I have mentioned that neither the ion chamber nor the in-core detector signals are sufficiently accurate to be used directly, that is without some correction, for the purpose of controlling reactor power, particularly when that power becomes significant at and above 5%FP. While the neutron flux is the "primary" variable of concern, the power generated by that neutron flux is both the useful output and the parameter that needs to accurately measured and controlled. Although one can compute the relationship between neutron flux and power output, it is desirable to have a continuous and accurate measure of the thermal power produced by the reactor. In this section we look at the two principal means of measuring the thermal power output of the reactor.

(1) Heat Output from the Reactor

The useful heat output of a CANDU reactor appears in the fuel channels, in the form of heat transferred from the fuel to the heat transport system coolant. This heat is subsequently transferred to the light water on the secondary side of the steam generators. There are therefore two principal places for measuring the thermal output of the reactor: one is the heat transferred to the coolant as if flows through the reactor, and the other is the heat transferred to the feedwater between the time it enters the steam generator until it leaves as steam. Let us look at measuring the heat transfer in the reactor first.

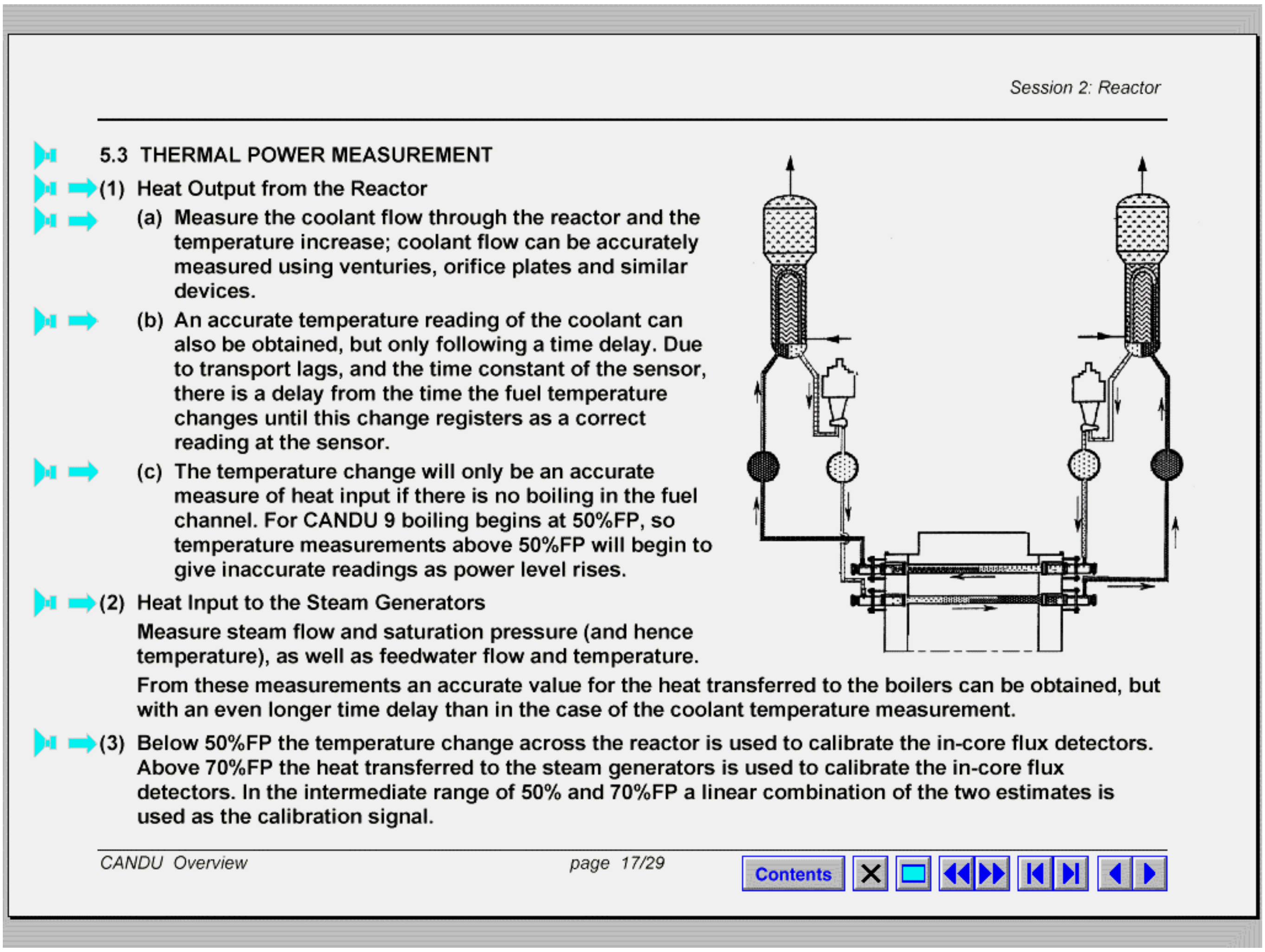
(a) The heat transferred from the fuel coolant can be determined by measuring the flow rate and the temperature difference between fuel channel inlet and outlet. The coolant flow can be accurately measured using venturies, orifice plates and similar devices, and in any case is fairly constant throughout the power levels of interest.

(b) Accurate temperature readings of the coolant at the fuel channel inlet and outlet can also be obtained, but only following a time delay. The temperature measurements are made with Resistance Temperature Detectros (RTDs) mounted on the feeder pipes. Due to the time it takes for the coolant to reach the detector, called the transport lag, and the time constant of the sensor itself, there is a delay from the time the fuel temperature changes until this change registers as a correct reading at the RTDs.

(c) An even bigger problem with this method of measuring heat transfer is that the temperature change will only be an accurate measure of heat input if there is no boiling in the fuel channel. For CANDU 9 boiling begins at 50%FP, so temperature measurements above 50%FP will begin to give inaccurate readings as power level rises. Therefore, to determine thermal power above 50%FP, we need to look at the suitability of using the measurements across the steam generators.

(2) Heat Input to the Steam Generators

By measuring steam flow and temperature, as well as feedwater flow and temperature, the amount of heat transferred across the steam generators can be determined. Because the steam is at saturation conditions, it is in fact easier to measure steam pressure and compute the corresponding temperature. From these measurements an accurate value for the heat transferred to the boilers can be obtained, but the transport lag is much longer than in the case of the coolant temperature measurement.



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5.3 THERMAL POWER MEASUREMENT

(1) Heat Output from the Reactor

(a) Measure the coolant flow through the reactor and the temperature increase; coolant flow can be accurately measured using venturies, orifice plates and similar devices.

(b) An accurate temperature reading of the coolant can also be obtained, but only following a time delay. Due to transport lags, and the time constant of the sensor, there is a delay from the time the fuel temperature changes until this change registers as a correct reading at the sensor.

(c) The temperature change will only be an accurate measure of heat input if there is no boiling in the fuel channel. For CANDU 9 boiling begins at 50%FP, so temperature measurements above 50%FP will begin to give inaccurate readings as power level rises.

(2) Heat Input to the Steam Generators

Measure steam flow and saturation pressure (and hence temperature), as well as feedwater flow and temperature.

From these measurements an accurate value for the heat transferred to the boilers can be obtained, but with an even longer time delay than in the case of the coolant temperature measurement.

(3) Below 50%FP the temperature change across the reactor is used to calibrate the in-core flux detectors. Above 70%FP the heat transferred to the steam generators is used to calibrate the in-core flux detectors. In the intermediate range of 50% and 70%FP a linear combination of the two estimates is used as the calibration signal.

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(3) A combination of the above two measurements is needed to cover the complete power range. Below 50%FP the temperature change across the reactor is used, and above 70%FP the heat transferred to the steam generators is used to determine reactor thermal power. In the intermediate range of 50% and 70%FP a linear combination of the two estimates is used to obtain a smooth transfer from one signal source to the other, as shown on the diagram.

5.4 REACTOR POWER MEASUREMENT

A nuclear reactor operates over a very wide range of neutron flux levels. During initial start-up it can be as low as 10^{-14} of full power. Special start-up instruments that are not installed permanently are used at these very low levels. We will not deal with these in this course.

The neutron flux levels that need to be measured by the permanently installed instruments read flux levels from 10^{-5} to 150% of full power. It is very difficult to obtain accurate measurements over such a wide range. The type of instruments available and the restrictions on their placement result in additional difficulties in making accurate neutron flux and reactor power measurements. For these reasons a number of different devices and techniques are used to determine the flux distribution and the total power level of the reactor.

(1) Ion Chambers

The wide range of flux measurements are provided by three sets of ion chamber units. They are located on the outside of the calandria shell at arrow (1), and are therefore able to provide only an indirect measure of the average neutron flux inside the reactor. The ion chamber signal is processed by the instrumentation system, at arrow (2), to supply the following measurements to the Reactor Regulating System:

- log neutron power, 10^{-5} to 150% full power;
- linear neutron power, 0 to 150% full power;
- rate of change of log power, -15% to +15% of present power per second.

(2) Flux Detectors

In order to measure the neutron flux distribution inside the reactor, flux detectors are distributed throughout the core (arrow 1). These self-powered detectors cannot measure flux values below about 1%FP, and are used therefore to provide measurements of the local flux between 10% and 120% full power. The signals from these detectors are processed to give a linear measure of the neutron flux, both locally and for the overall power level of the reactor.

There are two types of in-core detectors, one uses Vanadium (arrow 2) and the other Platinum (arrow 3) as the detector material. The sheaths of both types are made of Inconel.

(a) Platinum flux detectors have fast response to changes in neutron flux, and can be used as the input signal to the Regulating System to control neutron power between 15% and 100%FP. Both the spatial flux distribution and the total reactor power level are controlled on the basis of the Platinum detectors.

The only problem with these detectors is that they respond not only to neutrons but also to gamma rays. In order to use these signals for reactor power level control, the signals from the Platinum detectors must be adjusted to remove the contribution of the gamma rays.

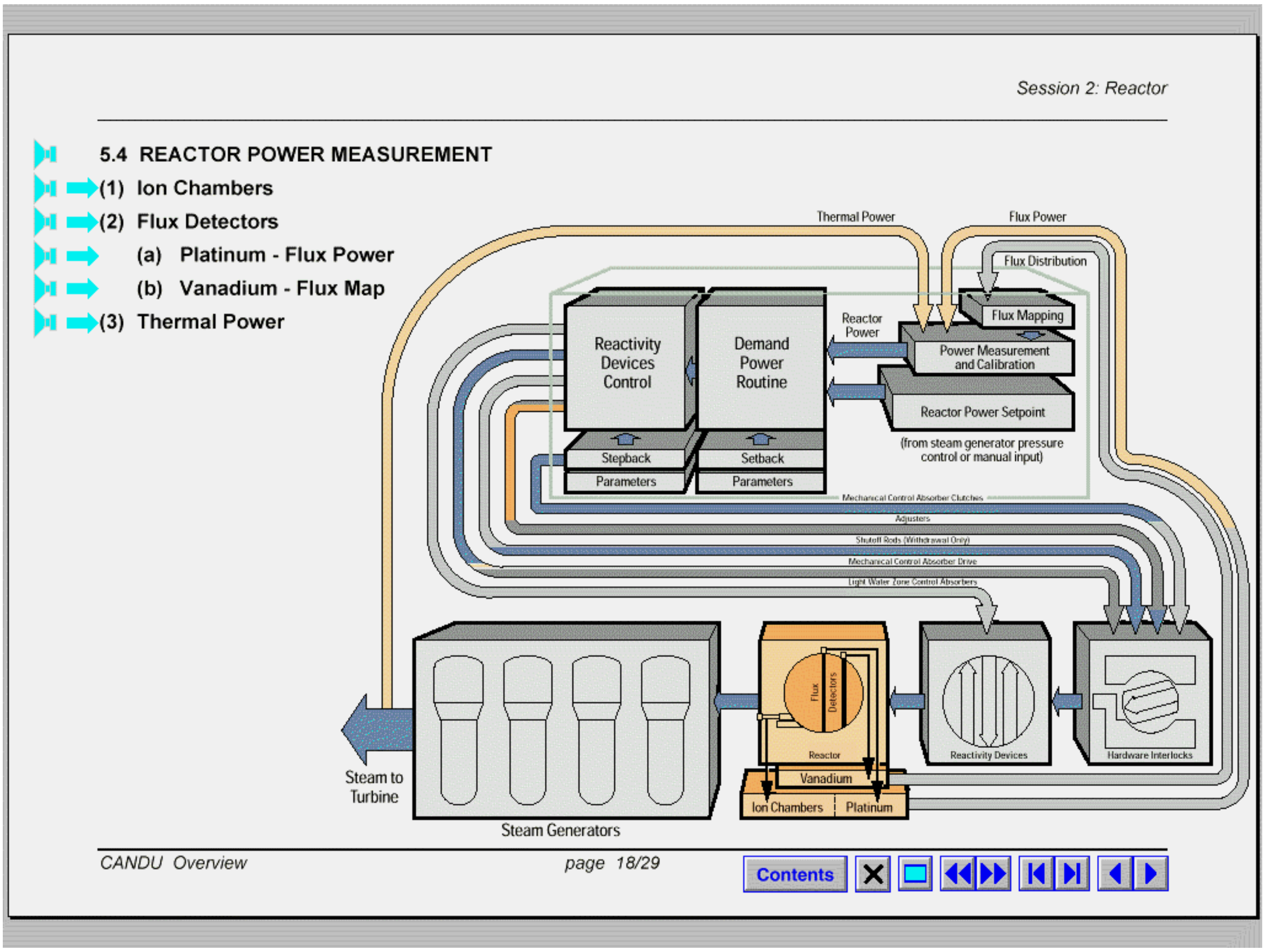
(b) The Vanadium flux detectors have the advantage that they are only sensitive to neutrons, but they cannot be used directly for reactor power control because of a relatively slow response to changes in neutron flux. The dominant time constant is about five minutes.

The Vanadium detectors are used as inputs to a flux mapping program, the output of which is used, along with the Thermal Power measurements, to adjust the Platinum detector readings for spatial flux control.

(3) Thermal Power

As noted earlier, because of their sensitivity to gamma rays, the Platinum in-core flux detector signals must be adjusted to ensure that an accurate measure of the neutron flux is obtained. The Platinum detector signals are calibrated by the use of thermal power measurements taken on the secondary side of the Steam Generators.

Steam flow, steam pressure, feedwater flow and feedwater temperature measurements are used to calculate the thermal power that is being transferred to the light water. This thermal power is a measure of the power produced by the reactor, although the signals will be delayed relative to the actual reactor power by approximately 20 seconds, due to thermal time constants and transport time. This delay does not effect the use of the thermal power measurement in calibrating the Platinum signal for the purpose of overall reactor power control.



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5.4 REACTOR POWER MEASUREMENT

- **(1) Ion Chambers**
- **(2) Flux Detectors**
  - **(a) Platinum - Flux Power**
  - **(b) Vanadium - Flux Map**
- **(3) Thermal Power**

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6. SIMPLIFIED REACTOR REGULATING SYSTEM BLOCK DIAGRAM

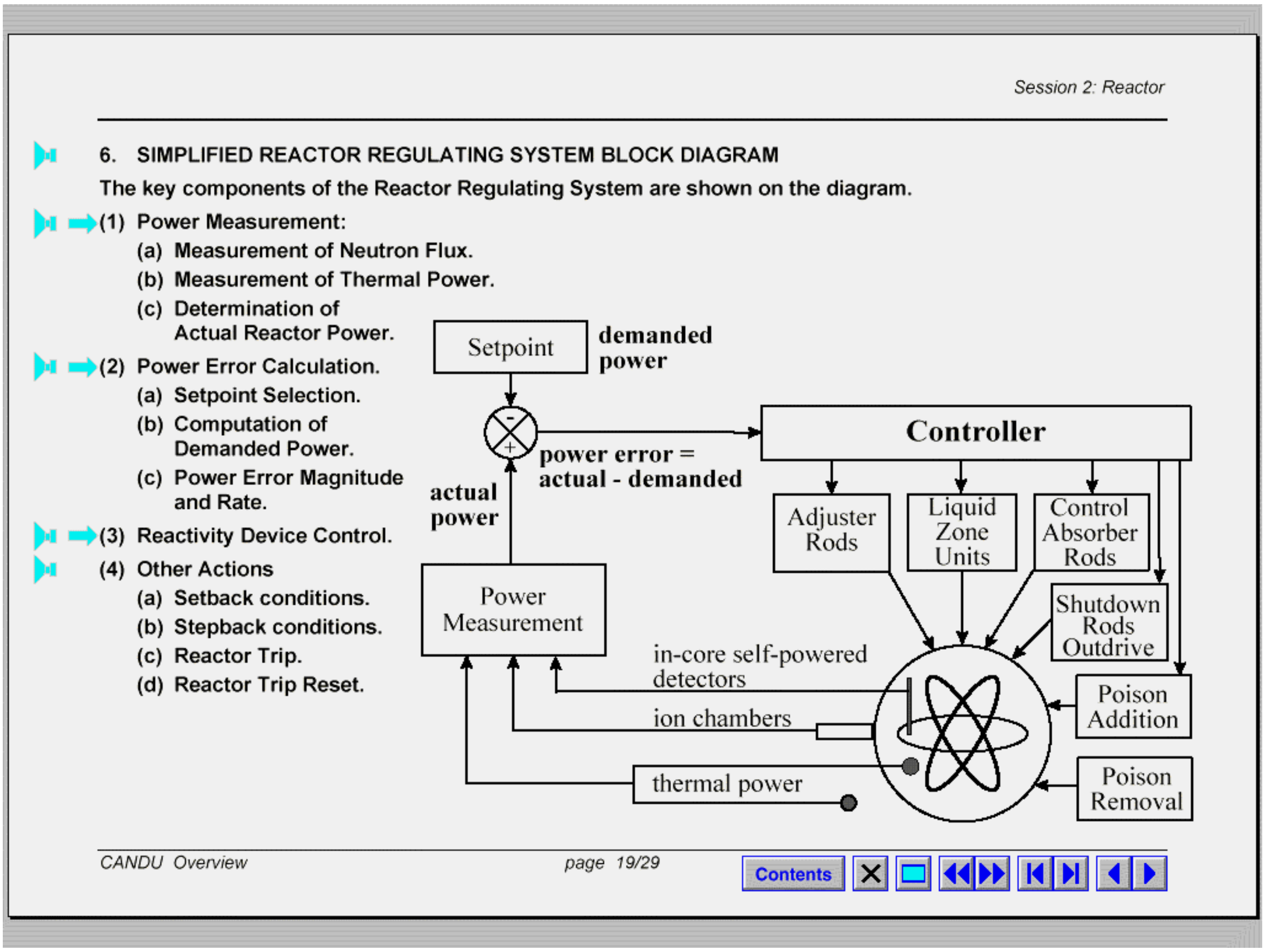
This simplified diagram shows the key components of the Reactor Regulating System. These are the Power Measurement, including both neutron and thermal power measurements, the computation of Power Error as the difference between Actual and Demanded Power, the Controller Algorithm that determines the response of the reactivity mechanisms to the power error, and certain other actions that can override the normal operation of the reactor regulating system.

(1) We have studied in the previous sections how the various instruments and methods for measuring both reactor neutron and thermal power, and why no single measure of reactor power is acceptable as the basis of reactor control. I will only mention a few of the key factors here.

(a) In-core flux detectors provide a direct measure of the neutron flux in the reactor. By distributing these detectors in the core, the local flux in the 14 control zones, as well as at some 100 locations in the core can be measured. These measurements provide the basis for both spatial and overall reactor power control between 5%FP and 120%FP. However, because of gamma radiation and detector time constant, these measurements need to be calibrated against thermal power measurements to achieve the desired accuracy. Also, at power levels below 5%, the in-core flux detector do not provide a sufficient signal strength, so at low power levels the neutron flux is measured by ion chambers. These instruments are located just outside the calandria, so they measure the leakage flux, and therefore their readings are not an accurate measure of either the average flux or of its distribution in the core. However, at low power levels, and for rate of change of flux measurements, neither of these shortfalls is a problem.

(b) As I mentioned in item (1a), the in-core flux detector readings need to be calibrated against direct measurements of thermal power. Such measurements can be made at the reactor, by knowing the coolant flow and its temperature change across the reactor. Such a measurement will give an accurate value for heat transferred from the fuel to the coolant, provided no boiling of the coolant takes place. In CANDU 9 boiling begins at 50 degrees centigrade, so above this power level an alternate method of thermal power measurement is needed. This is provided by measuring the heat transferred to the feedwater in the steam generator, by measuring feedwater flow and temperature and steam flow and pressure. From the steam pressure reading the temperature can be calculated, since the steam is at saturation conditions. The computation of heat transferred across the steam generator is more accurate at higher power levels, so there is a transfer of thermal power computation from the reactor measurements to the steam generator measurements between 50-70%FP, and above 70%FP, thermal power measurement is based entirely on the steam generator parameters.

(c) Actual Reactor Power is computed by continuously calibrating the in-core flux detector readings by the thermal power measurements. Although the latter are delayed by transport lag and sensor time constant, these delays are not significant as long as reactor power changes near 1200%FP are taken at the slower rates. For the purpose of spatial flux control, the 14 zone flux detector signals are corrected on a several minute long time scale by the Flux Mapping program.



Session 2: Reactor

6. SIMPLIFIED REACTOR REGULATING SYSTEM BLOCK DIAGRAM

The key components of the Reactor Regulating System are shown on the diagram.

(1) Power Measurement:
  (a) Measurement of Neutron Flux.
  (b) Measurement of Thermal Power.
  (c) Determination of Actual Reactor Power.
(2) Power Error Calculation.
  (a) Setpoint Selection.
  (b) Computation of Demanded Power.
  (c) Power Error Magnitude and Rate.
(3) Reactivity Device Control.
(4) Other Actions
  (a) Setback conditions.
  (b) Stepback conditions.
  (c) Reactor Trip.
  (d) Reactor Trip Reset.

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(2) As we will see later in this Session, Power Error is a key parameter in determining the actions of the Reactor Regulating System. Calculation of the Power Error involves more than just subtracting demanded power from actual power.

(a) As you know from Session 1, the Reactor Power Setpoint is specified by the Steam Generator Pressure Control program if the unit is in Normal Mode, and by the Operator if the unit is in Alternate Mode of control. Both the target value of the setpoint and the desired rate of power level change are specified.

(b) From the specified target reactor power setpoint and its rate of change the Demanded Power Routine in RRS calculates the value of Demanded Power for each iteration of the computer program. Various limits are designed into the routine to ensure that reactor power is maneuvered at safe rates.

(c) The reactor power control algorithm has both a proportional term and a rate term. The proportional term is the difference between the magnitudes of actual and demanded power. The rate term is the difference between the rate of change of actual and demanded power. The effective power error is the sum of these two terms. When we say “power error”, we mean this “effective power error”.

(3) The power error is the basis for determining which Reactivity Control Device to move and by what amount. The word “move” is appropriate not only for the solid control rods, but also for the liquid zones and for poison addition, since in each of these cases the control signal moves the appropriate control valve. This movement is usually expressed in terms of valve “lift” as the pneumatic controller effective raises or lowers the valve stem.

(4) As we will see in this Session, the actions of the controller can be influenced by and at times overridden by certain conditions. We will look at the following special conditions: Setback, Stepback, Reactor Trip and the Reset of a Reactor Trip

6.1 OVERVIEW OF THE CONTROL ALGORITHMS

(1) The five main components of the CANDU Reactor Regulating System control algorithms are highlighted on the diagram. They are the selection of the Reactor Power Setpoint, Measurement of Actual Reactor Power, Calculation of Power Error, Control of the Reactivity Devices, and Reactor Stepback.

(2) In Session 1 we looked at the two main sources of the Reactor setpoint. You recall that in Normal Mode, reactor power setpoint is determined by the steam generator pressure control program, so as to eliminate steam generator pressure error. The rate is always the same, 0.4%FP/sec

In Alternate Mode, the unit operator specifies via the keyboard the reactor power setpoint, and its rate of change.

There are two other possible sources of the reactor power setpoint, and both of these will override the previous two. Hold Power, as its name suggests, will stop any power changes and makes the setpoint equal to the demanded power at the time the Hold Power action was initiated.

Reactor Setback will make the setpoint equal to a value determined by the conditions indicating the need for a Setback, and will specify the rate of reduction that is also a function of the Setback conditions.

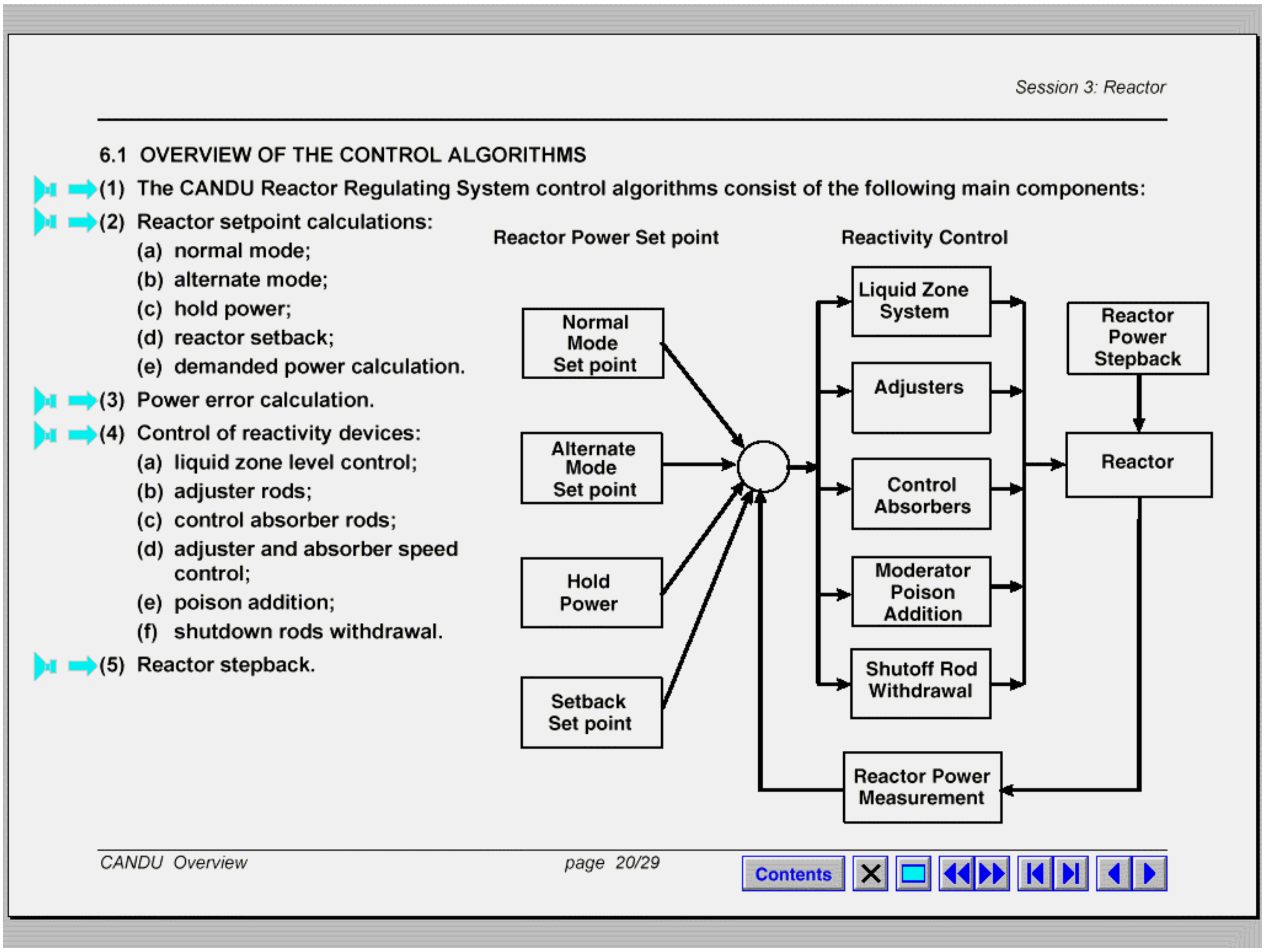
When I talk about the Reactor Setpoint, what I really mean is the target value to which reactor power should be raised. It would not be safe to request a sudden step increase in reactor power, so the target setpoint is reached at the specified rate. It is the Demanded Power routine which calculates for each computer iteration the incremental increase towards the target setpoint. The Demanded Power routine is executed every 0.5 second, and on each iteration the appropriate increment is added to or subtracted from the value of demanded power that was computed in the previous iteration. For example a rate of setpoint increase of 0.4%FP/second will result in Demanded Power increasing by 0.2%FP on each iteration, until Demanded Power reaches the Target Setpoint.

(3) The Power Error Calculation is done for each of the 14 zones and for the total or bulk reactor power. In this course we will concern ourselves principally with the bulk power error only. This is the parameter that determines the main reactor regulating system actions, particularly when the liquid zones alone are not capable to provide the required change in reactivity.

(4) As we will see in considerable detail later in this Session, the power error is the basic parameter that determines the movement of the reactivity control devices, although the average zone level also has an important role on the nature of the control action taken.

For small changes in power error, and as long as the liquid zone levels are neither too empty nor too full, changes in liquid zone controller levels are the first and often the only reactivity mechanism actions needed to eliminate the power error.

If the average zone level falls too low, and/or the power error is excessively negative, in other words there is need for positive reactivity in the core, withdrawal of the adjuster rods will be initiated by RRS.



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6.1 OVERVIEW OF THE CONTROL ALGORITHMS

(1) The CANDU Reactor Regulating System control algorithms consist of the following main components:

(2) Reactor setpoint calculations:
  (a) normal mode;
  (b) alternate mode;
  (c) hold power;
  (d) reactor setback;
  (e) demanded power calculation.

(3) Power error calculation.

(4) Control of reactivity devices:
  (a) liquid zone level control;
  (b) adjuster rods;
  (c) control absorber rods;
  (d) adjuster and absorber speed control;
  (e) poison addition;
  (f) shutdown rods withdrawal.

(5) Reactor stepback.

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6.2 DEMANDED POWER ROUTINE

In the Demanded Power Routine of the Reactor Regulating System program the value of Demanded Reactor Power, which is in fact the value of the reactor power setpoint for that computer iteration, is calculated from the power change that was determined by the Reactor Setpoint program I described in the previous section.

The diagram illustrates the various factors that the program uses. The horizontal axis shows time in seconds and the vertical axis Reactor Power in %FP. The example illustrates the case of a power increase in ALTERNATE MODE.

(1) The example is for a change in Target Reactor Power Setpoint from 70%FP to 80%FP at a rate of 0.8%FP/sec. The specified Target Reactor Power Setpoint is shown as a step change by the blue lines. Such a big change would cause an excessively large power error, so the Demanded Power level change is instead achieved by ramping the instantaneous setpoint up to the target value at the specified rate, in this example 0.8%FP/sec.

(2) The Demanded Power Routine executes once in every 0.5 second. On each iteration the amount of change in demanded power is computed as a constant times the difference between the target and current values of the setpoint, and added to the value of demanded power from the previous iteration.

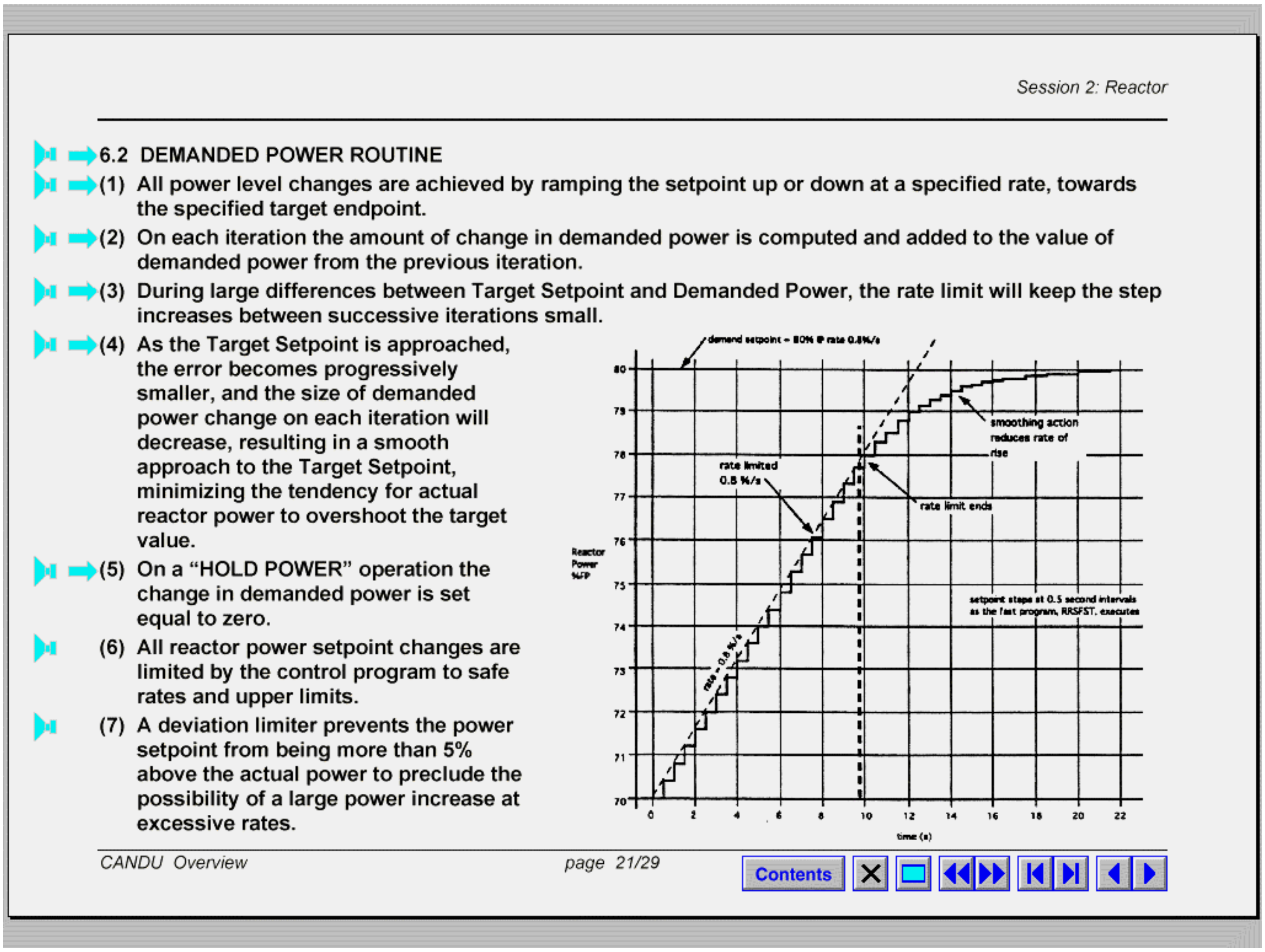
(3) During large differences between Target Setpoint and Demanded Power, the specified rate of setpoint change is used as an upper limit on the step size per iteration, keeping the step changes between successive iterations small. Since the rate is specified per second, half of the nominal rate is the maximum amount that can be added on each program iteration. In the example, the maximum step increase in Demanded Power is 0.4%FP on each iteration.

(4) As the Target Setpoint is approached, the difference between Target Setpoint and Demanded Power becomes progressively smaller, and the size of demanded power change on each iteration will decrease, resulting in a smooth approach to the Target Setpoint, minimizing the tendency for actual reactor power to overshoot the target value.

(5) The diagram illustrates what happens on a “HOLD POWER” operation. In the upper part of the diagram you can see the step-wise increase in Demanded Power towards the Power Setpoint Target. In the lower part you see what happens on the iteration following the pressing of the HOLD POWER button: the Power Setpoint Target is set equal to the value Demanded Power has on that iteration, and the change in demanded power is stopped.

(6) Although it may be possible for the operator to enter on the keyboard a incorrect values of Target Reactor Power Setpoint and Rate, the actual reactor power setpoint changes are limited by the control program to safe rates and upper limits.

(7) Another part of the program includes a deviation limiter, which prevents the power setpoint from being more than 5% above the actual power. This feature is designed to preclude the possibility of a large power increase at excessive rates.



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6.2 DEMANDED POWER ROUTINE

(1) All power level changes are achieved by ramping the setpoint up or down at a specified rate, towards the specified target endpoint.

(2) On each iteration the amount of change in demanded power is computed and added to the value of demanded power from the previous iteration.

(3) During large differences between Target Setpoint and Demanded Power, the rate limit will keep the step increases between successive iterations small.

(4) As the Target Setpoint is approached, the error becomes progressively smaller, and the size of demanded power change on each iteration will decrease, resulting in a smooth approach to the Target Setpoint, minimizing the tendency for actual reactor power to overshoot the target value.

(5) On a “HOLD POWER” operation the change in demanded power is set equal to zero.

(6) All reactor power setpoint changes are limited by the control program to safe rates and upper limits.

(7) A deviation limiter prevents the power setpoint from being more than 5% above the actual power to preclude the possibility of a large power increase at excessive rates.

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6.3 POWER ERROR CALCULATION

(1) The bulk power error is a measure of the difference between the measured power and the demanded power of the reactor, plus a rate of change of power error term.

power error = k1(actual power - demanded power) + k2(actual rate - demanded rate)

The unit of power error is %FP. In terms of control system design, this is a proportional plus derivative type of controller. The difference between actual and demanded power is the proportional term, and constants k1 is the proportional gain. The difference between the actual and demanded rates is the derivative term, and k2 the derivative gain constant.

This is a very important relationship, as it has a fundamental role in RRS determining the movements of reactivity devices.

(2) The sign of the power error determines whether to

(a) increase or decrease the levels of the zones

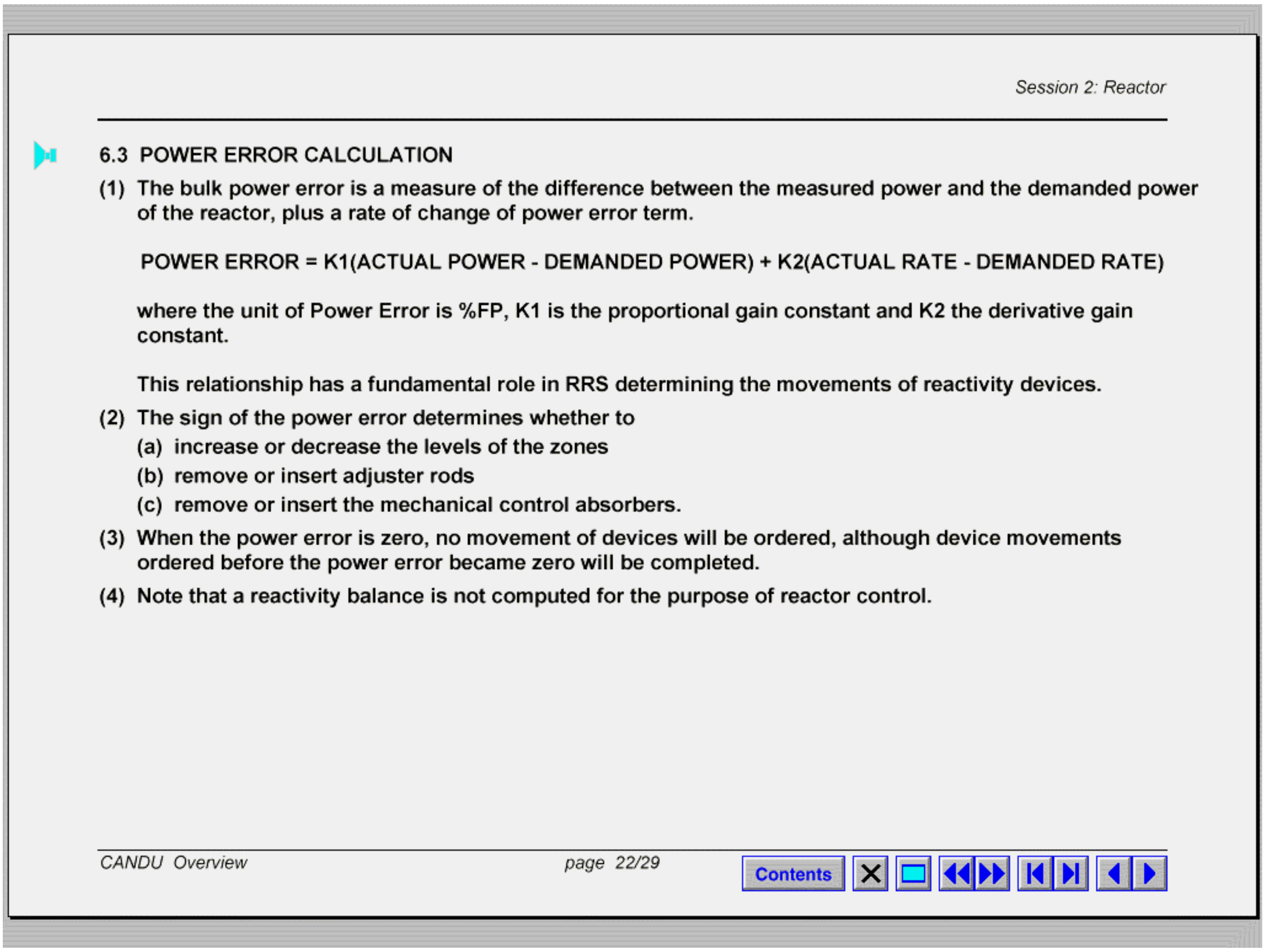
(b) remove or insert adjuster rods

(c) remove or insert the mechanical control absorbers.

We will see the decision rules for each of these reactivity mechanism actions in the next few sections.

(3) When the power error is zero, no movement of devices will be ordered, although device movements ordered before the error became zero will be completed.

(4) Note that reactor power control is based entirely on the measurements of neutron and thermal power. Although the method of control is by varying the reactivity worth of the various control mechanisms, the actual value of reactivity or of reactivity error is not computed in order to achieve reactor control.



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6.3 POWER ERROR CALCULATION

(1) The bulk power error is a measure of the difference between the measured power and the demanded power of the reactor, plus a rate of change of power error term.

POWER ERROR = K1(ACTUAL POWER - DEMANDED POWER) + K2(ACTUAL RATE - DEMANDED RATE)

where the unit of Power Error is %FP, K1 is the proportional gain constant and K2 the derivative gain constant.

This relationship has a fundamental role in RRS determining the movements of reactivity devices.

(2) The sign of the power error determines whether to
  (a) increase or decrease the levels of the zones
  (b) remove or insert adjuster rods
  (c) remove or insert the mechanical control absorbers.

(3) When the power error is zero, no movement of devices will be ordered, although device movements ordered before the power error became zero will be completed.

(4) Note that a reactivity balance is not computed for the purpose of reactor control.

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6.4 SETBACK ROUTINE

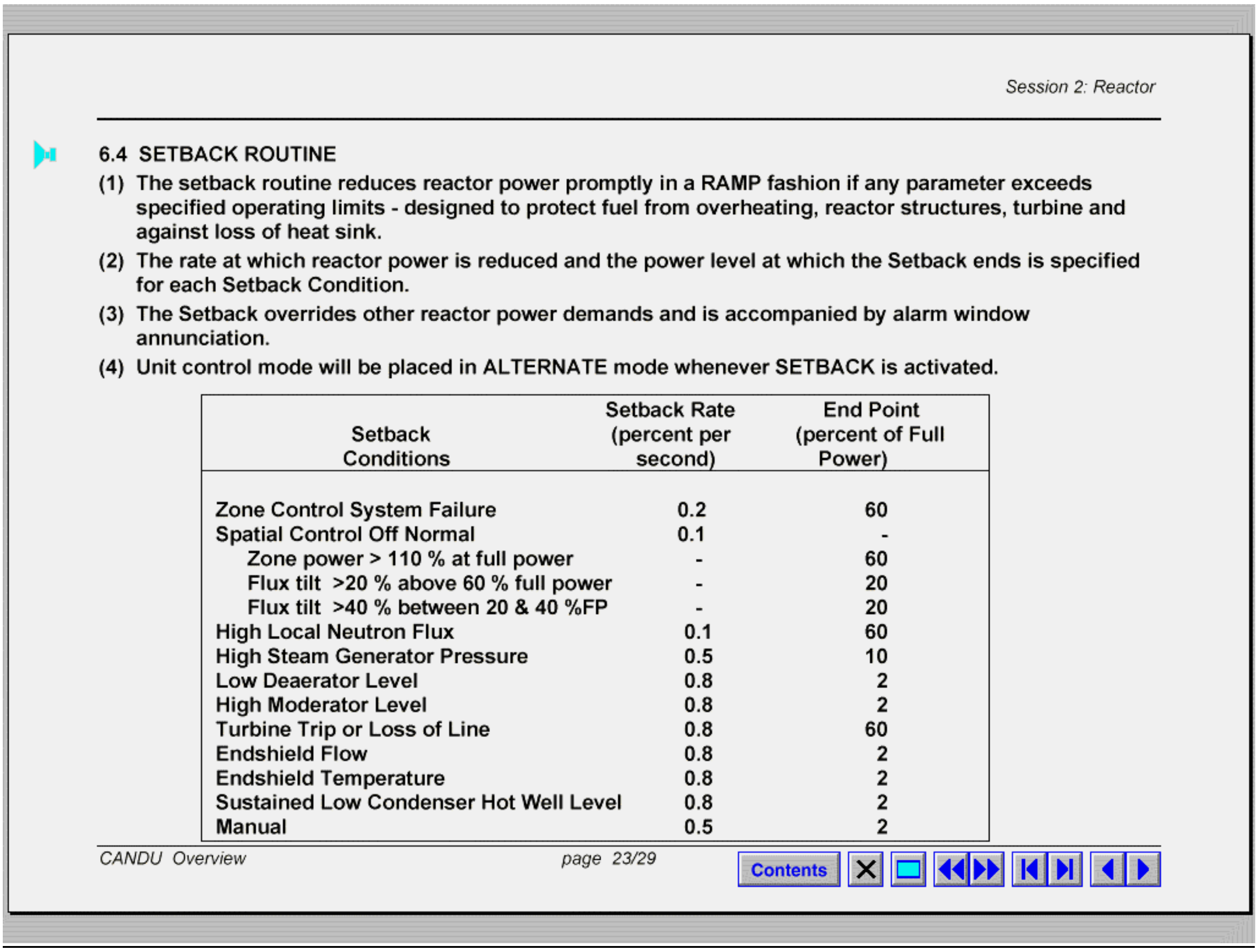
(1) The setback routine reduces reactor power promptly in a RAMP fashion if any parameter exceeds specified operating limits. These conditions are designed to protect the fuel from overheating, to protect the various reactor structures, to protect the turbine, and to protect against any loss of heat sink. In each case the Setback is activated to ensure that the reactor is controlled to safe power levels and that the fuel is cooled at all times.

(2) The rate at which reactor power is reduced and the power level at which the setback ends are specified for each Setback condition..

(3) The setback overrides other reactor power demands and is accompanied by alarm window annunciation.

(4) Unit control mode will be placed in ALTERNATE mode whenever SETBACK is activated.

Setback Conditions	Setback Rate (percent per second)	End Point (percent of Full Power)
Zone Control System Failure	0.2	60
Spatial Control Off Normal	0.1	-
Zone power > 110 % at full power	-	60
Flux tilt >20 % above 60 % full power	-	20
Flux tilt >40 % between 20 & 40 %FP	-	20
High Local Neutron Flux	0.1	60
High Steam Generator Pressure	0.5	10
Low Deaerator Level	0.8	2
High Moderator Level	0.8	2
Turbine Trip or Loss of Line	0.8	60
End Shield Flow	0.8	2
End Shield Temperature	0.8	2
Sustained Low Condenser Hot Well Level	0.8	2
Manual	0.5	2



Session 2: Reactor

6.4 SETBACK ROUTINE

(1) The setback routine reduces reactor power promptly in a RAMP fashion if any parameter exceeds specified operating limits - designed to protect fuel from overheating, reactor structures, turbine and against loss of heat sink.

(2) The rate at which reactor power is reduced and the power level at which the Setback ends is specified for each Setback Condition.

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Flux tilt >20 % above 60 % full power	-	20
Flux tilt >40 % between 20 & 40 %FP	-	20
High Local Neutron Flux	0.1	60
High Steam Generator Pressure	0.5	10
Low Deaerator Level	0.8	2
High Moderator Level	0.8	2
Turbine Trip or Loss of Line	0.8	60
Endshield Flow	0.8	2
Endshield Temperature	0.8	2
Sustained Low Condenser Hot Well Level	0.8	2
Manual	0.5	2

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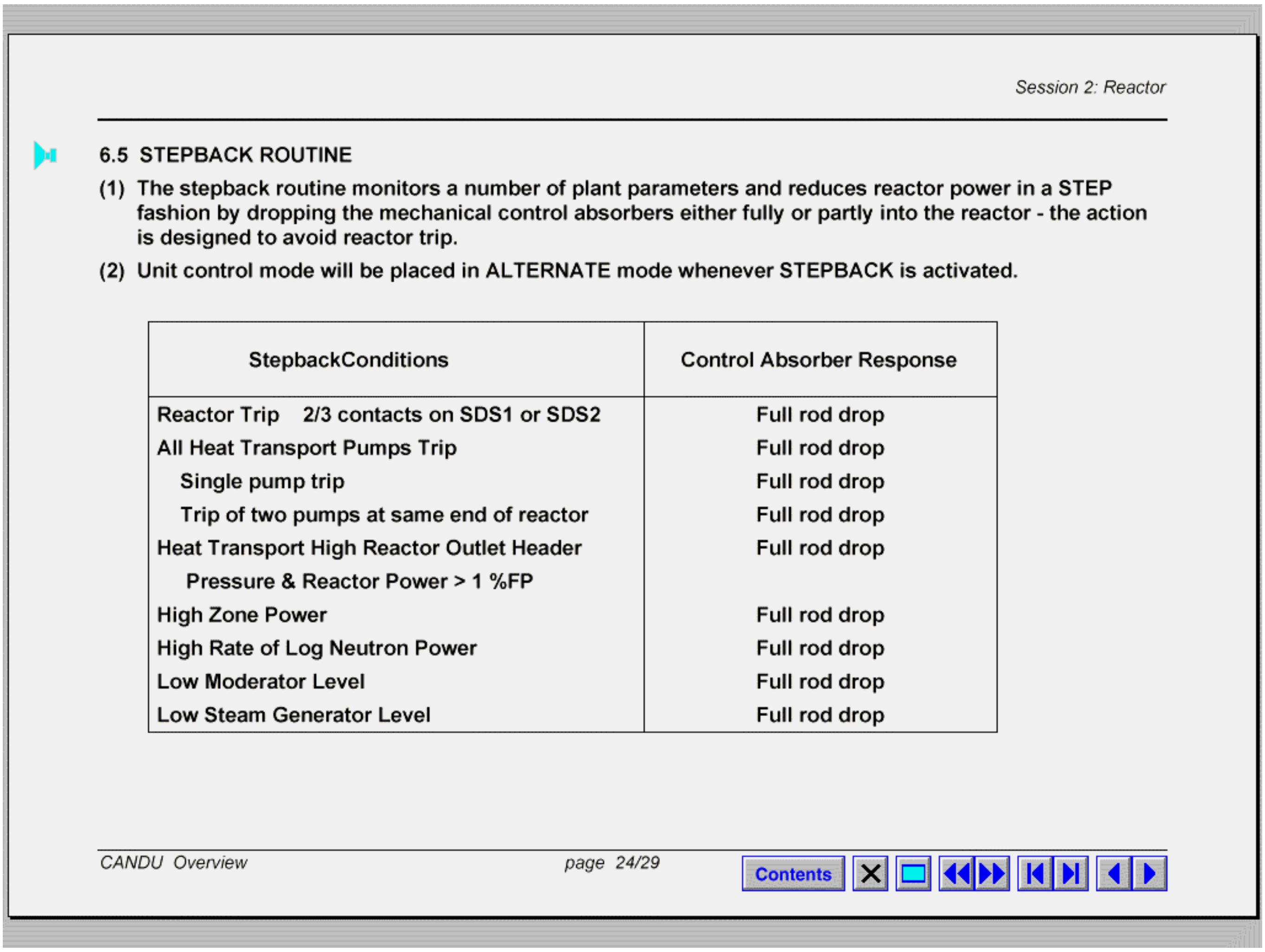
6.5 STEPBACK ROUTINE

(1) The Stepback Routine monitors a number of plant parameters and reduces reactor power in a STEP fashion by dropping the mechanical control absorbers either fully or partly into the reactor. In principal, the actions of the Stepback function are designed to avoid a reactor trip. However, if a reactor trip does occur, the Stepback function is activated, so that all the control absorbers will be dropped into the core, thereby aiding the rapid shutdown of the reactor.

(2) Unit control mode will be placed in ALTERNATE mode whenever STEPBACK is activated.

Stepback Conditions	Control Absorber Response
Reactor Trip 2/3 contacts on SDS1 or SDS2	Full rod drop
All Heat Transport Pumps Trip	Full rod drop
Single pump trip	Full rod drop
Trip of two pumps at same end of reactor	Full rod drop
Heat Transport High Reactor Outlet Header Pressure & Reactor Power > 1 %FP	Full rod drop
High Zone Power	Full rod drop
High Rate of Log Neutron Power	Full rod drop
Low Moderator Level	Full rod drop
Low Steam Generator Level	Full rod drop



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6.5 STEPBACK ROUTINE

(1) The stepback routine monitors a number of plant parameters and reduces reactor power in a STEP fashion by dropping the mechanical control absorbers either fully or partly into the reactor - the action is designed to avoid reactor trip.

(2) Unit control mode will be placed in ALTERNATE mode whenever STEPBACK is activated.

StepbackConditions	Control Absorber Response
Reactor Trip 2/3 contacts on SDS1 or SDS2	Full rod drop
All Heat Transport Pumps Trip	Full rod drop
Single pump trip	Full rod drop
Trip of two pumps at same end of reactor	Full rod drop
Heat Transport High Reactor Outlet Header Pressure & Reactor Power > 1 %FP	Full rod drop
High Zone Power	Full rod drop
High Rate of Log Neutron Power	Full rod drop
Low Moderator Level	Full rod drop
Low Steam Generator Level	Full rod drop

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7. REACTIVITY DEVICE CONTROL

The method of reactivity device control in CANDUs can be illustrated by the diagram shown on this and subsequent pages. It shows power error in %FP on the horizontal axis and average zone level on the vertical axis.

Inside the region shown in blue, that is for power errors between –4 and +3%FP and average liquid zone levels between 15 and 80%, reactor power control is achieved by the actions of the liquid zone control system. Outside this region, as we will see, the actions of the liquid zones are supplemented by adjuster and control absorber rod movements.

(1) Let us remind ourselves of the reactivity control devices available to the Reactor Regulating System. The primary method of short-term reactivity control is by varying the liquid level in the zone controllers. As illustrated in the diagram, under normal operating conditions the adjusters, shown in maroon, are fully inserted, the control absorbers, coloured green, are fully withdrawn and the average liquid zone control compartment level, in blue, is around 50%. If the zones are unable to provide the required reactivity effect, other devices are operated by the reactor regulating system.

(2) A shortage of negative reactivity will be indicated by either

  (a) a high zone controller level, that is the average zone level is above 80% full, or

  (b) a positive power error. Remember that this is he effective power error, that is it includes both the proportional and he derivative terms;

(c) both cases indicate insufficient negative reactivity, and will cause the mechanical control absorbers to be driven into the core, one bank at a time; if any adjusters are not fully in the core, they too will be inserted.

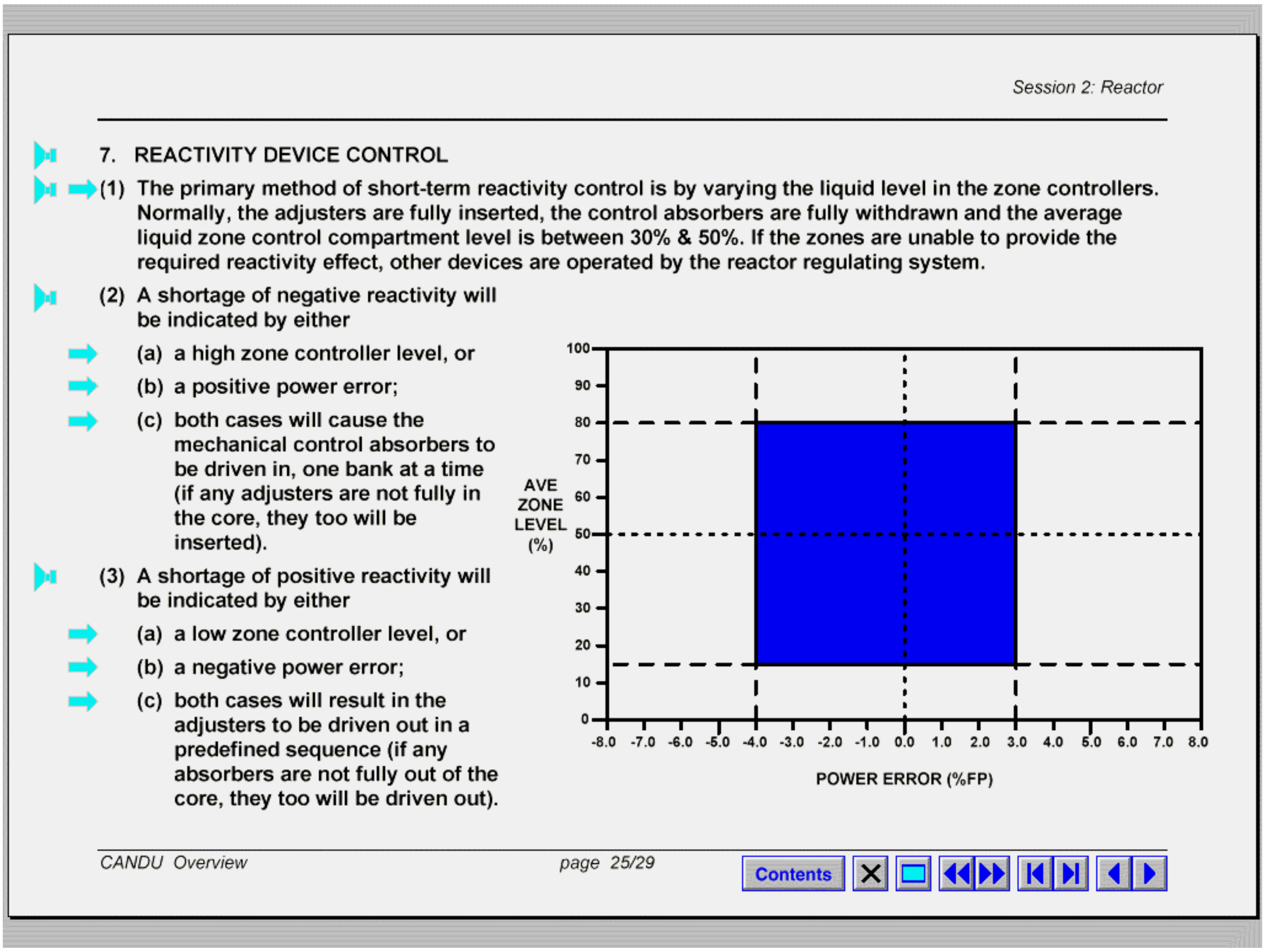
(3) A shortage of positive reactivity will be indicated by either

(a) a low zone controller level, that is the average zone level is below 15%, or

(b) a negative power error. You should be noticing that there is an area of overlap between the regions of low zone level and negative power error, as there was in the case of high; zone level and positive power error.

(c) Both cases of low zone levels and negative power error will result in the adjusters to be driven out of the core in a predefined sequence, and if any absorbers are not fully out of the core, they too will be driven out.

In the next two sections we take a closer look at the logic that drives adjuster and control absorber rods.



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7. REACTIVITY DEVICE CONTROL

(1) The primary method of short-term reactivity control is by varying the liquid level in the zone controllers. Normally, the adjusters are fully inserted, the control absorbers are fully withdrawn and the average liquid zone control compartment level is between 30% & 50%. If the zones are unable to provide the required reactivity effect, other devices are operated by the reactor regulating system.

(2) A shortage of negative reactivity will be indicated by either

- **(a) a high zone controller level, or**
- **(b) a positive power error;**
- **(c) both cases will cause the mechanical control absorbers to be driven in, one bank at a time (if any adjusters are not fully in the core, they too will be inserted).**

(3) A shortage of positive reactivity will be indicated by either

- **(a) a low zone controller level, or**
- **(b) a negative power error;**
- **(c) both cases will result in the adjusters to be driven out in a predefined sequence (if any absorbers are not fully out of the core, they too will be driven out).**

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7.1 ADJUSTER RODS

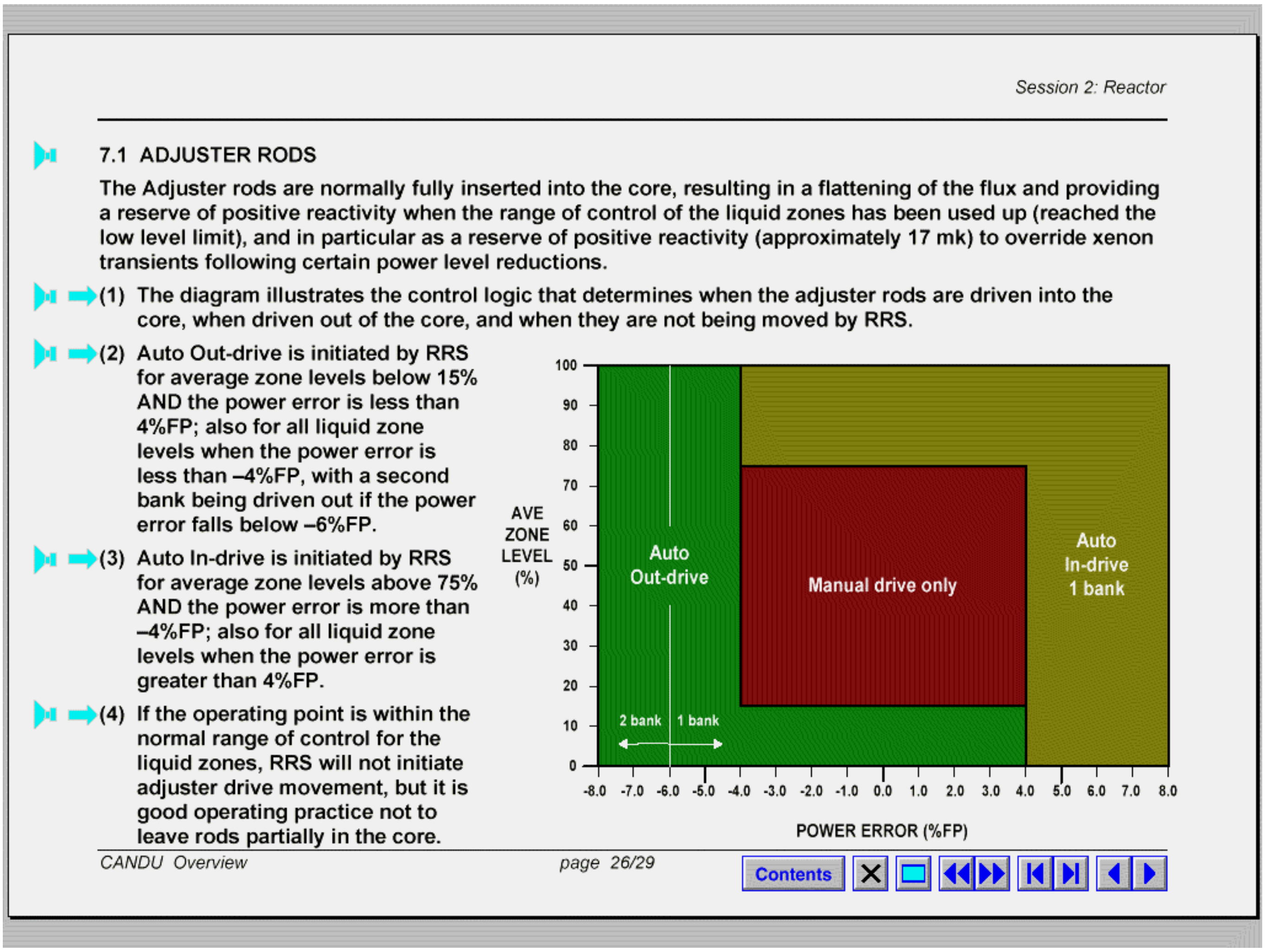
As we have seen, the Adjuster rods are normally fully inserted into the core, so as to flatten the neutron flux and to provide a reserve of positive reactivity when the range of control of the liquid zones has been used up, that is they have reached their low level limit, and in particular as a reserve of positive reactivity, approximately 17 mk, to override xenon transients following certain power level reductions.

(1) The diagram illustrates the control logic that determines when the adjuster rods are driven into the core, when they are driven out of the core, and when they are not being moved by RRS. In all cases, the movement of the adjuster rods is designed to return the operating point, that is the intersection of power error and average zone level, to the central region, shown in maroon colour on this diagram.

(2) Auto out-drive is initiated by RRS for average zone levels below 15% AND for power errors less than 4%FP; also for all liquid zone levels when the power error is less than –4%FP, with a second bank being drive out if the power error falls below –6%FP. Note that I am using AND in capital letters as the logical operator.

(3) Auto in-drive is initiated by RRS for average zone levels above 75% AND for power errors that are more than –4%FP; also for all liquid zone levels when the power error is greater than 4%FP.

(4) If the operating point is within the normal range of control for the liquid zones, RRS will not initiate adjuster drive movement, but it is good operating practice not to leave rods partially in the core. It is important to remember that for the operation of the CANDU Simulator, the maximum reactor power that is allowed without the risk of fuel damage, is reduced by 5% for each bank of adjuster rods that are not fully inserted into the core. Since there are eight banks of rods, with all of them fully or at least partially withdrawn, maximum power should be limited to 60%FP. This restriction is not part of the Reactor Regulating System, nor will be any indications of problems by the simulation, but should be observed by you at all times as you operate the Simulator as a matter of good operating practice.



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7.1 ADJUSTER RODS

The Adjuster rods are normally fully inserted into the core, resulting in a flattening of the flux and providing a reserve of positive reactivity when the range of control of the liquid zones has been used up (reached the low level limit), and in particular as a reserve of positive reactivity (approximately 17 mk) to override xenon transients following certain power level reductions.

(1) The diagram illustrates the control logic that determines when the adjuster rods are driven into the core, when driven out of the core, and when they are not being moved by RRS.

(2) Auto Out-drive is initiated by RRS for average zone levels below 15% AND the power error is less than 4%FP; also for all liquid zone levels when the power error is less than –4%FP, with a second bank being driven out if the power error falls below –6%FP.

(3) Auto In-drive is initiated by RRS for average zone levels above 75% AND the power error is more than –4%FP; also for all liquid zone levels when the power error is greater than 4%FP.

(4) If the operating point is within the normal range of control for the liquid zones, RRS will not initiate adjuster drive movement, but it is good operating practice not to leave rods partially in the core.

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7.2 CONTROL ABSORBER RODS

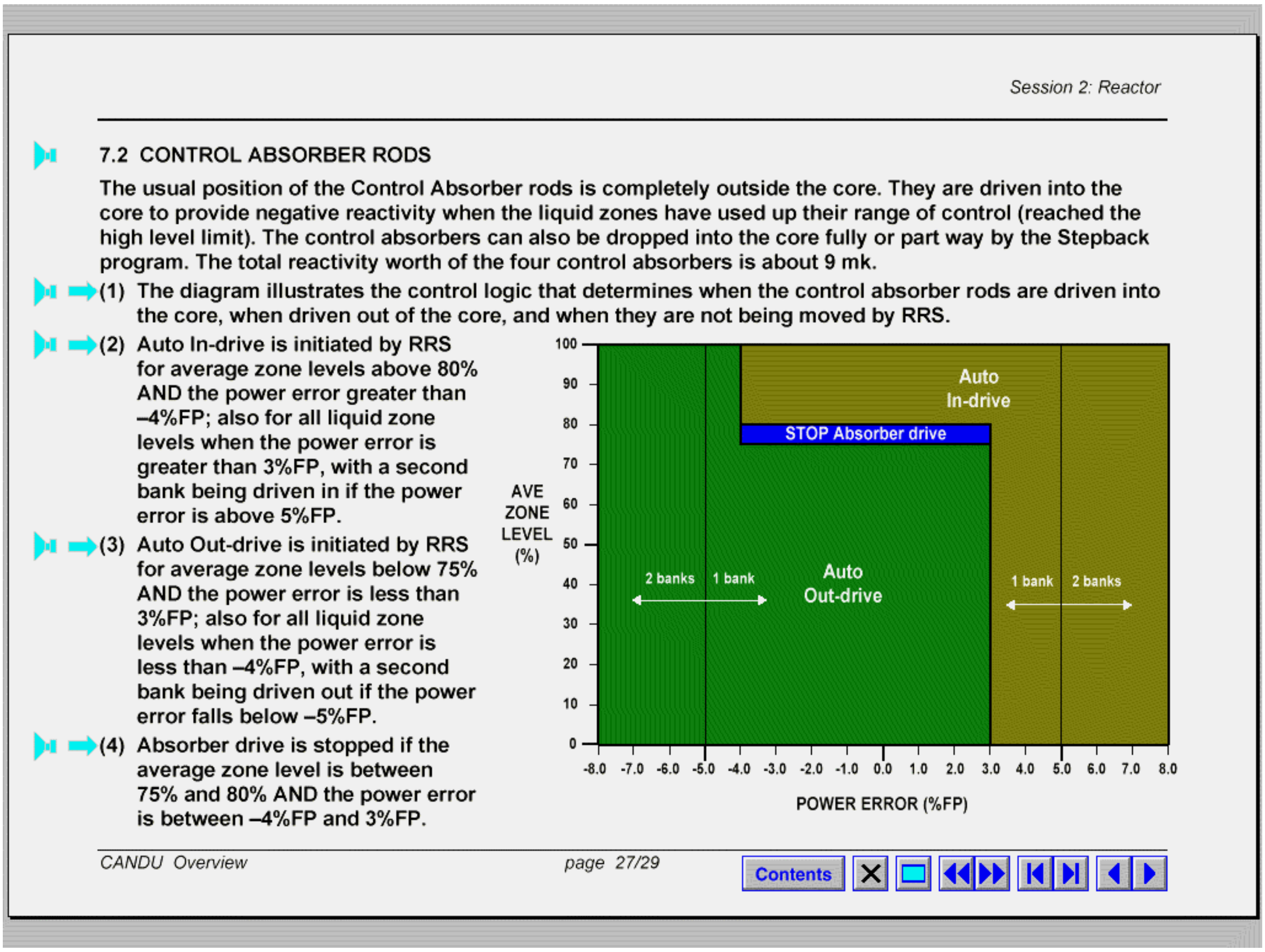
You will recall that the usual position of the Control Absorber rods is completely outside the core. They are driven into the core to provide negative reactivity when the liquid zones have used up their range of control, that is they have reached their high level limit. The control absorbers can also be dropped into the core fully or part way by the Stepback program. The total reactivity worth of the four control absorbers is about 9 mk.

(1) The diagram illustrates the control logic that determines when the control absorber rods are driven into the core, when driven out of the core, and when they are not being moved by RRS.

(2) Auto In-drive is initiated by RRS for average zone levels above 80% AND the power error greater than –4%FP; also for all liquid zone levels when the power error is greater than 3%FP, with a second bank being driven in if the power error is above 5%FP.

(3) Auto Out-drive is initiated by RRS for average zone levels below 75% AND the power error is less than 3%FP; also for all liquid zone levels when the power error is less than –4%FP, with a second bank being driven out if the power error falls below –5%FP.

(4) Absorber drive is stopped if the average zone level is between 75% and 80% AND the power error is between –4%FP and 3%FP.



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7.2 CONTROL ABSORBER RODS

The usual position of the Control Absorber rods is completely outside the core. They are driven into the core to provide negative reactivity when the liquid zones have used up their range of control (reached the high level limit). The control absorbers can also be dropped into the core fully or part way by the Stepback program. The total reactivity worth of the four control absorbers is about 9 mk.

(1) The diagram illustrates the control logic that determines when the control absorber rods are driven into the core, when driven out of the core, and when they are not being moved by RRS.

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(4) Absorber drive is stopped if the average zone level is between 75% and 80% AND the power error is between –4%FP and 3%FP.

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7.3 SHUTDOWN ROD WITHDRAWAL LOGIC

Although the Shutdown Rods are part of Reactor Shutdown System #1, and as such are to be fully independent of the Reactor Regulating System, the latter is used for the purpose of withdrawing the Shutdown Rods. Independence is maintained by separating the motor that drives out the shutdown rods under the control of RRS by a clutch from the shaft of the rod withdrawing mechanism by a clutch, which is entirely under the control of SDS#1.

The reason for using RRS to withdraw the Shutdown Rods is to ensure that reactor power control is maintained during Shutdown Rod withdrawal, and that under no circumstance will the withdrawal of the Shutdown Rods result in the insertion of excessive amounts of reactivity.

The following are the factors that need to be understood and remembered for the withdrawal logic of the Shutdown Rods:

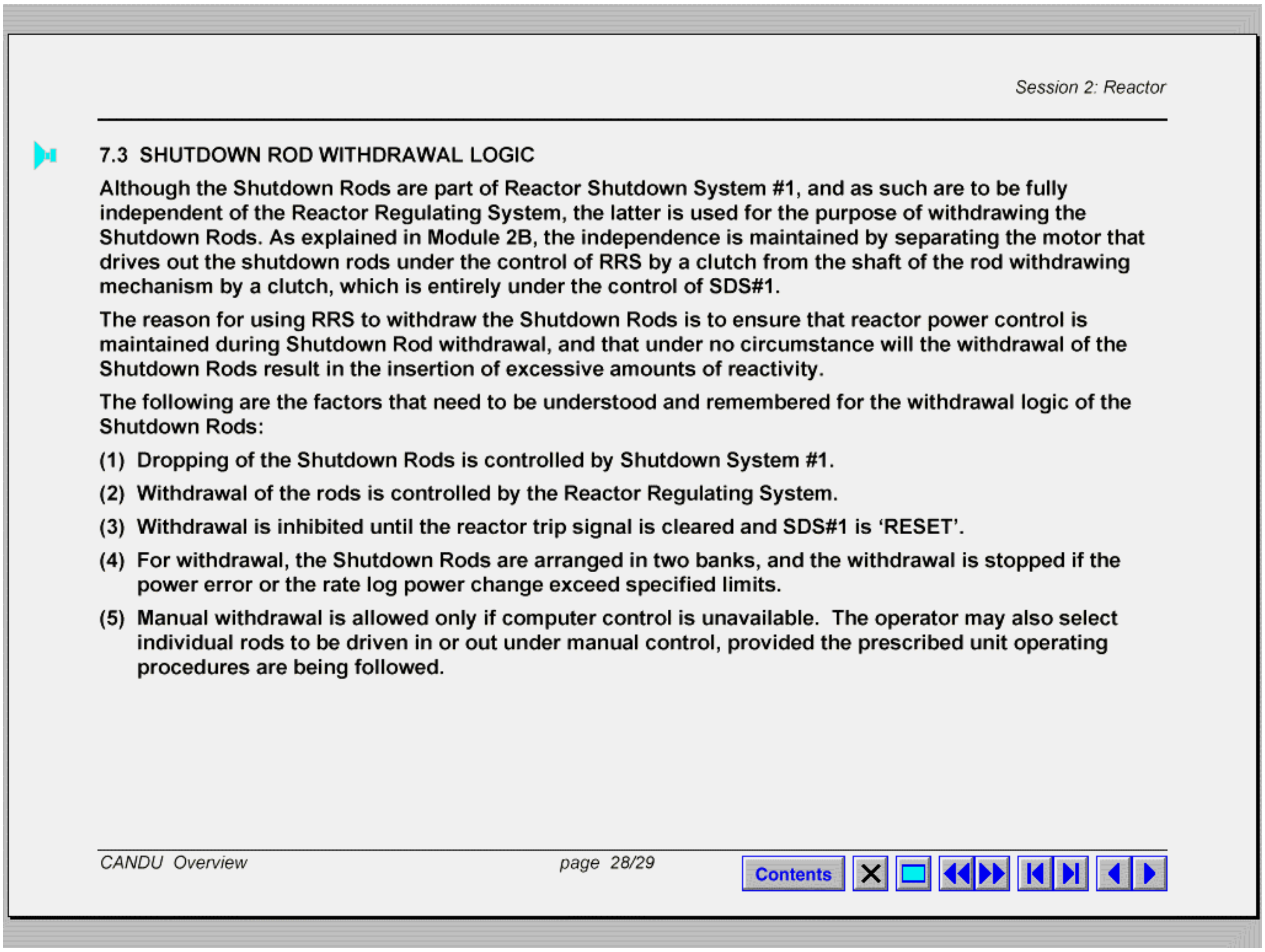
(1) Dropping of the shutdown rods is controlled by Shutdown System #1.

(2) Withdrawal of the rods is controlled by the Reactor Regulating System.

(3) Withdrawal is inhibited until the reactor trip signal is cleared and SDS#1 is ‘RESET’.

(4) For withdrawal, the Shutdown Rods are arranged in two banks, and the withdrawal is stopped if the power error or the rate log power change exceed specified limits.

(5) Manual withdrawal is allowed only if computer control is unavailable. The operator may also select individual rods to be driven in or out under manual control, provided the prescribed unit operating procedures are being followed.



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7.3 SHUTDOWN ROD WITHDRAWAL LOGIC

Although the Shutdown Rods are part of Reactor Shutdown System #1, and as such are to be fully independent of the Reactor Regulating System, the latter is used for the purpose of withdrawing the Shutdown Rods. As explained in Module 2B, the independence is maintained by separating the motor that drives out the shutdown rods under the control of RRS by a clutch from the shaft of the rod withdrawing mechanism by a clutch, which is entirely under the control of SDS#1.

The reason for using RRS to withdraw the Shutdown Rods is to ensure that reactor power control is maintained during Shutdown Rod withdrawal, and that under no circumstance will the withdrawal of the Shutdown Rods result in the insertion of excessive amounts of reactivity.

The following are the factors that need to be understood and remembered for the withdrawal logic of the Shutdown Rods:

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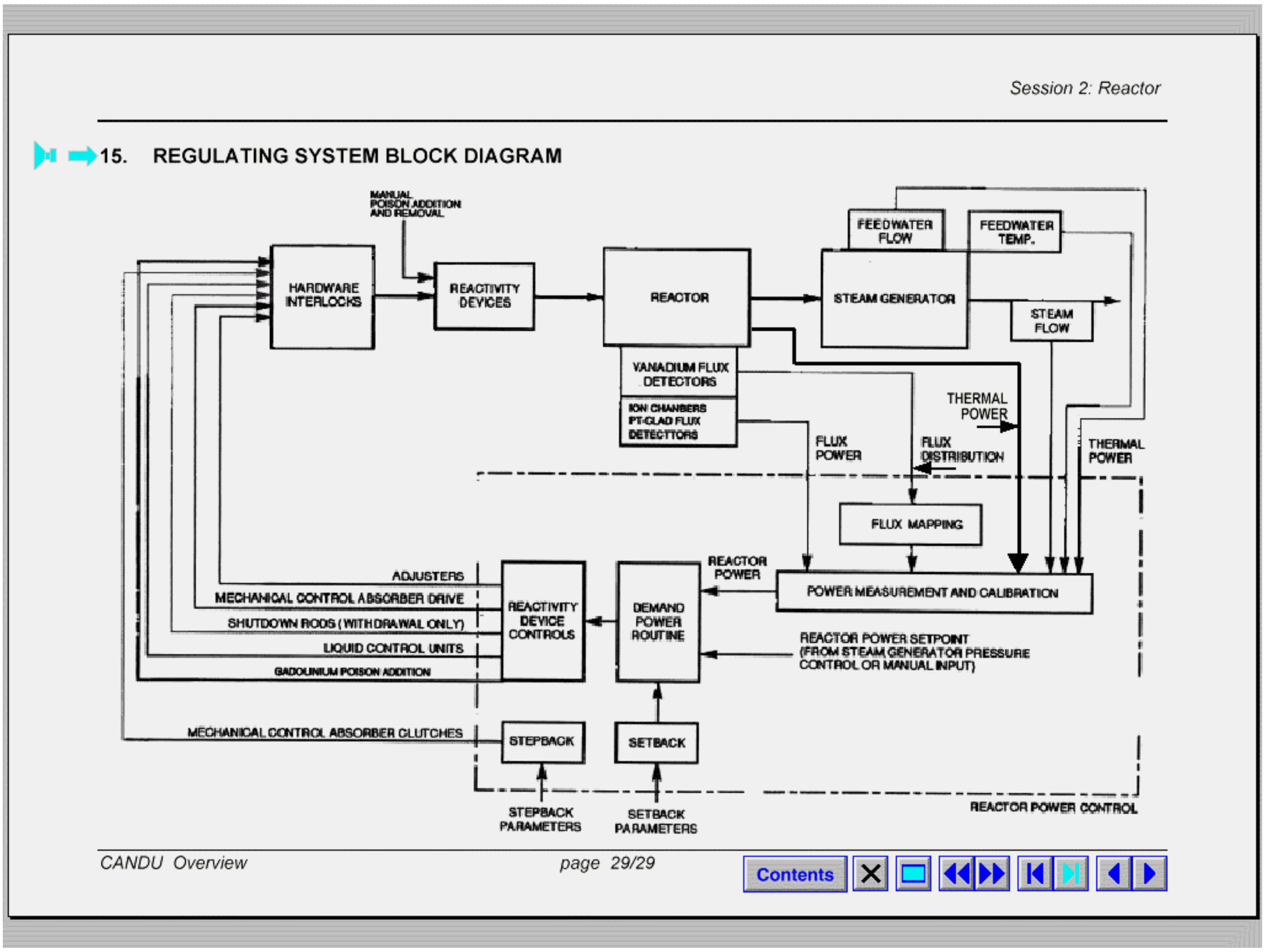
8. REGULATING SYSTEM BLOCK DIAGRAM

The diagram shows all the key components of the Reactor Regulating System that we have discussed in this Session. It is in the form of a feedback control loop, showing the processes being controlled, the parameters measured, the control algorithms and the final control elements.

The process measurements are taken from the Reactor, including neutronic and thermal power measurements, and from the Steam Generator. These two process blocks have been highlighted in a blue coloured frame.

The readings of the Vanadium Flux detectors are input to the Flux Mapping Program, the ion chamber and Platinum clad Inconel flux detector signals, along with coolant flow and temperature readings, feedwater flow and temperature, steam flow and pressure are all input to the Power Measurement and Calibration program. The blocks responsible for Reactor Power Control in RRS are enclosed by a red frame. Additional programs to implement Reactor Power Control are Demanded Power Routine, which receives the Reactor Power Setpoint for the given mode of operation, including Reactor Setback, compares it with the Actual Reactor Power value and computes the effective power error. Based on the sign and magnitude of the power error the Reactivity Device Controls program determines what signals to send to each of the reactivity control devices. In the case that a Reactor Stepback condition is detected, signal is sent to open the clutches holding the Mechanical Control Absorbers.

All the signals to the Reactivity Devices are connected via Hardware Interlocks, these two blocks being highlighted in orange frames. The change in position of the Reactivity Mechanisms, plus any Liquid Poison that may be manually added, will alter the reactivity and hence the neutron and thermal power of the core, thereby closing the control loop.



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15. REGULATING SYSTEM BLOCK DIAGRAM

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RRS OVERVIEW