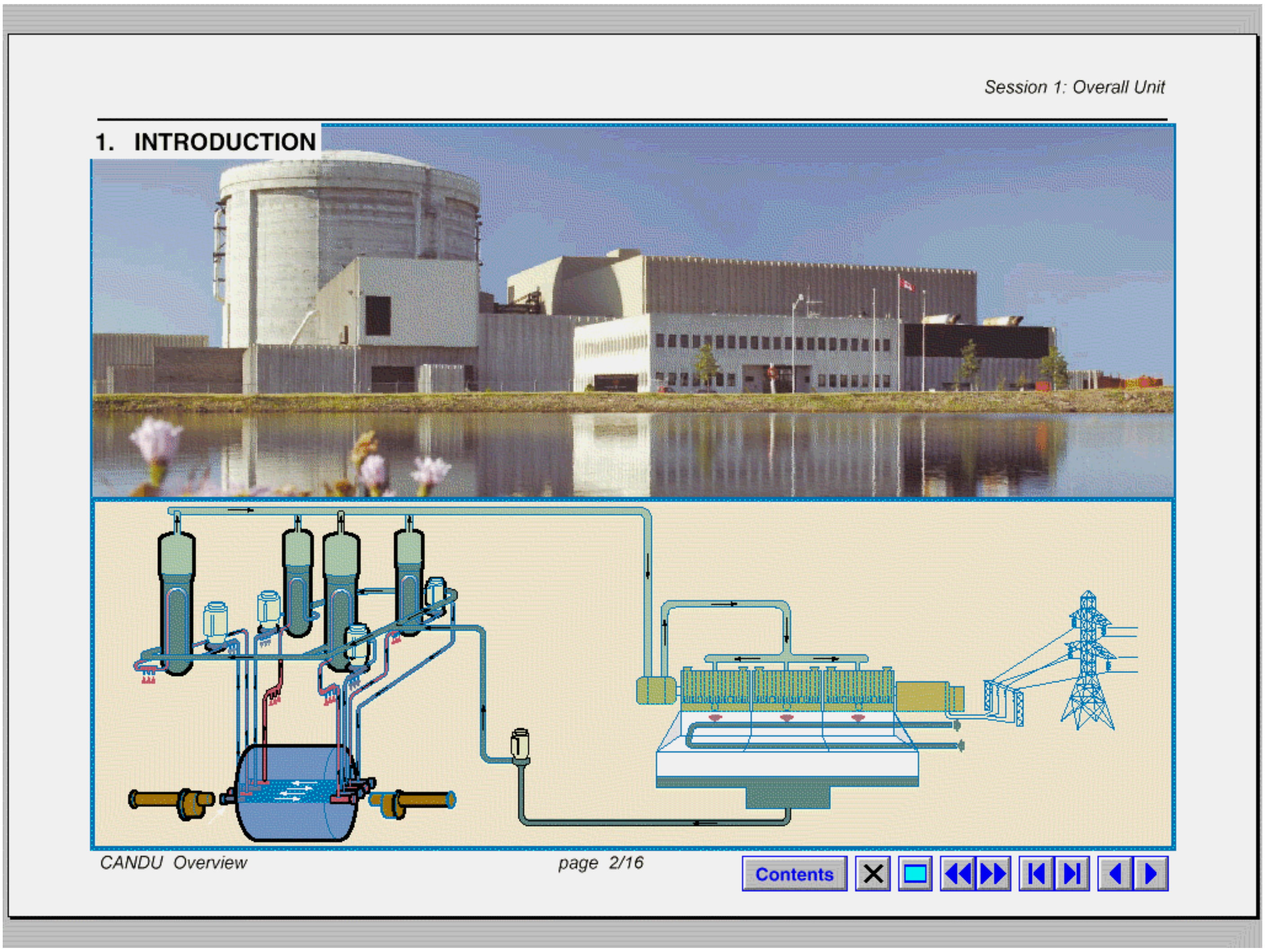
SESSION 1:



2. MAJOR CANDU SYSTEMS

The portion of this workshop that deals with CANDU Systems and Operations is organized into four Sessions. Each Session encompasses a major portion of a CANDU unit, and covers a system or a group of functionally related systems. The role and relation of the systems discussed in a Session to the overall generating unit is introduced and related to the rest of the Workshop with the aid of the "Course Map" shown on the diagram.

Item 1 In Session 1 we look at the Overall Nuclear Electric Generating Unit as an entity. I am using the yellow background in the diagram to illustrate what is meant by the term Overall Unit: it is the complete physical plant that is involved in having the energy in the nuclear fuel converted through various processes to electrical energy. This Session concentrates on the main building blocks that make up an operating unit and the interactions between these blocks.

Each of the subsequent Sessions will look at the main systems and groups of systems of the overall unit.

Item 2 In the second Session we look at the main components of the reactor and of the reactor regulating system.

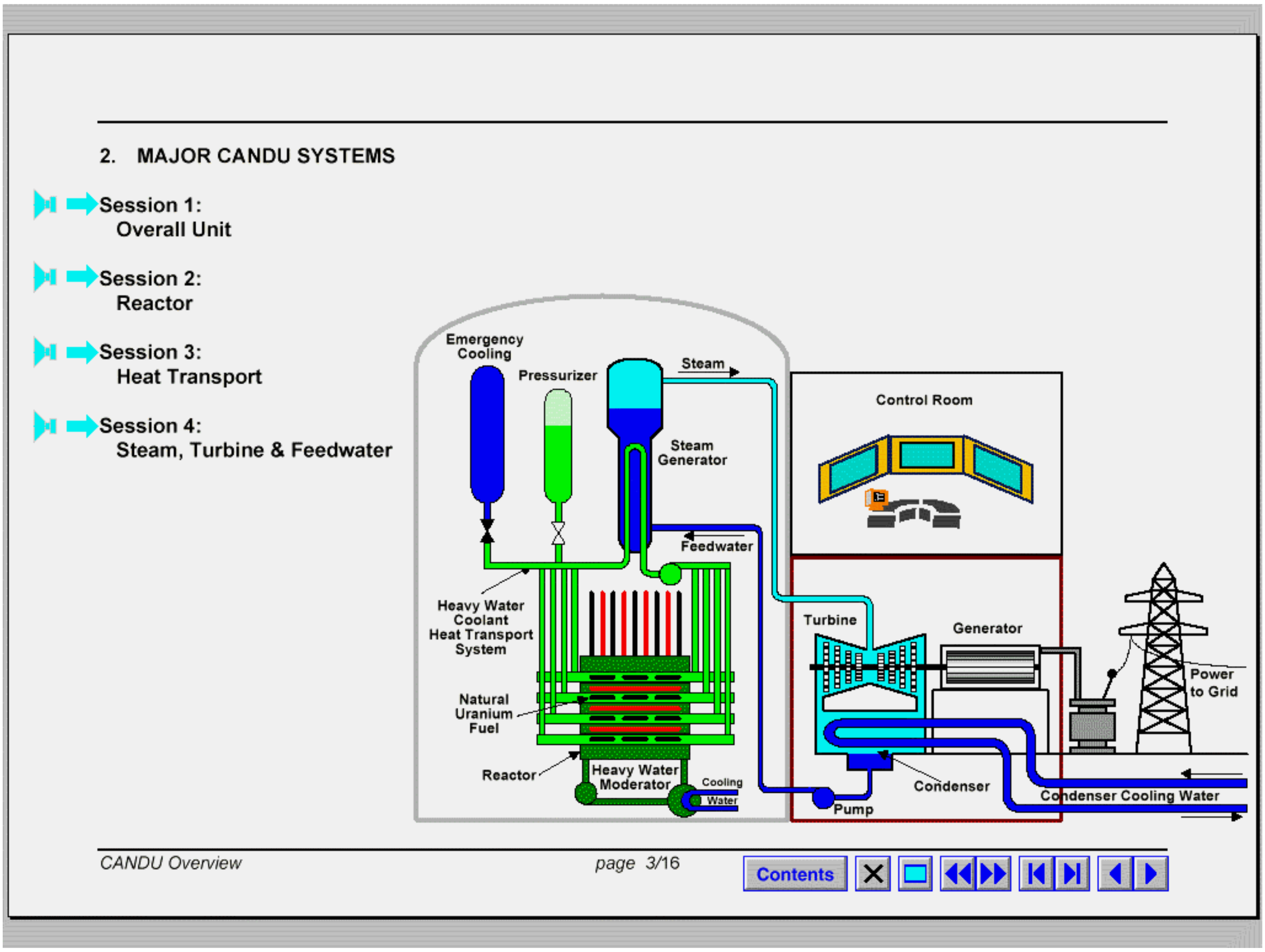
We will see how the natural uranium fuel is held in the fuel channels and how it is cooled by the heavy water of the heat transport system. We will also look at the types of instruments and techniques that are used to measure the power produced by the reactor, the control algorithms that compare the power measurements with the desired power level, and how the devices used to control the nuclear reaction change the power output of the reactor.

Using the simulator, you will perform several reactor operations under both normal and malfunction conditions, and gain a good appreciation of the rate and magnitude of power level changes, and the mechanisms through which the regulating system control reactor power.

Item 3 Session 3 is about the Heat Transport System, which in CANDUs uses heavy water to transfer the energy released by the nuclear fuel in the reactor to generate steam to drive the turbine and generator. You will learn the key features of the Main Circuit, how the pressure and inventory of heavy water is controlled in the heat transport system. It is quite a complex system, and it is shown in sufficient detail on the simulator to let you do some interesting exercises under normal as well as several malfunction conditions.

Item 4 Session 4 is about the systems that are often referred to collectively as the Balance of Plant: the steam, turbine and feedwater systems. Important control systems are associated with these, including the steam generator pressure and level control systems and the turbine control system.

On the simulator a variety of malfunctions involving each of the above systems will be dealt with.



3. NUCLEAR STEAM SUPPLY SYSTEM

The diagram shows the following major components of the CANDU Nuclear Steam Supply System, the Reactor, Fuel Handling, Heat Transport, Feedwater and Steam systems. The Fuel Handling System provides fresh fuel and removes spent fuel from the Reactor. The heat generated in the Reactor from the fissioning of nuclei in the fuel is removed by the Heat Transport system heavy water and is transferred in the Steam generators to the Feedwater, which is ordinary light water, and the resultant steam is supplied to the Turbine.

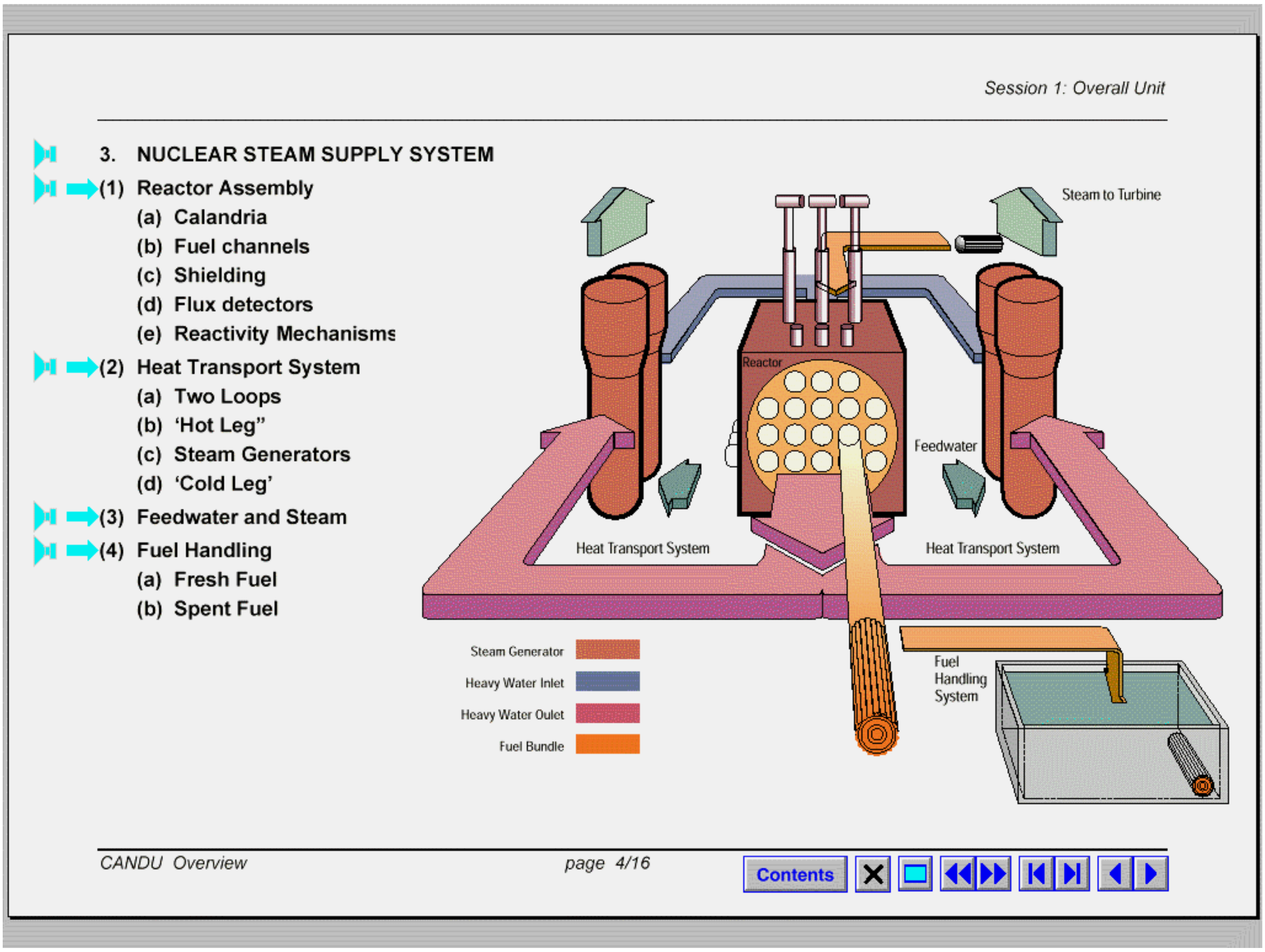
(1) The Reactor Assembly consists of (a) the Calandria, which is a stainless steel horizontal cylindrical vessel that holds the heavy water moderator and reflector. There are hundreds of Fuel Channels installed in the Calandria vessel and supported by the End Shield that close off the two ends of the Calandria. Arrow (b) points to one of the Fuel Channels, each of which consists of a calandria tube that surrounds a pressure tube that contains 12 natural uranium fuel bundles and carries the pressurized heavy water heat transport coolant. There are 380 such fuel channels in a CANDU 6 reactor, and 480 in a CANDU 9 reactor.

The Calandria is surrounded by a Shield Assembly, indicated by arrow (3), made of concrete and steel, and containing light water. There are In-core Flux Detectors installed from the top of the Calandria, and Ion Chambers that are housed at the side of the Calandria, as indicated by arrows (d). The Reactivity Mechanisms are shown by arrow (e) as being inserted from the top of the calandria.

(2) The Heat Transport System consists of two main loops, identified by the labels on the diagram. Each of the two loops has a ‘hot-leg’ as indicated by arrows (b1) and (b2), a pair of boilers in each loop, at arrows (c1) and (c2), and a ‘cold-leg’ shown at (d1) and (d2) to complete each loop. The actual system is of course much more complicated, with two circulating pumps per loop, reactor inlet and outlet headers and piping connections to every pressure tube. The heat transport coolant heavy water is continuously circulated through each loop, carrying the heat from the reactor to the steam generators and back to the reactor. The coolant is under high pressure so that only a small amount of boiling takes place near the outlets of the hottest fuel channels. We will look at the pressure and inventory control system, and other heat transport auxiliary systems later in this Session.

(3) The Steam Generators transfer the heat from the heavy water coolant of the heat transport system on the primary side to the light water on the secondary side to form steam. The steam is sent to the Balance Of Plant systems, most of it to the Turbine, and a much smaller amount to the Feed Heating system. After passing through the Turbine the steam is condensed in the Condenser, and the water is subsequently raised in temperature and pressure before returning it to the Steam Generators in the form of Feedwater.

(4) The Fuel Handling System takes fresh fuel bundles, as indicated by arrow (a) and feeds them into the designated fuel channel. After a residency time of approximately one year, the spent fuel bundles, indicated by arrow (b) are removed from the fuel channel by the computerized remote controlled fuel handling system, and transfers them to the irradiated fuel bay, where the bundles will reside for at least seven years, before they can be transferred to dry storage.



4. FUEL HANDLING AND STORAGE

Typical refuelling operations require that each day eight fuel bundles are replaced in one or two channels. Apart from the loading of new fuel bundles into the magazines of the new fuel ports, all other operations are controlled remotely from the control room using digital computers.

The Fuel Handling and Storage Facilities to support this operation include:

(1) receiving, storing, inspecting and loading new fuel into fuelling machines;

(2) on-line removal of spent fuel and insertion of fresh fuel;

(3) cooling of irradiated fuel during its removal and transfer to storage bays;

(4) underwater storage of irradiated fuel until it can be transferred to dry storage (at least six years).

(1) New fuel is received, inspected and stored in the New Fuel Storage room that is located in the Service Building.

When required for use in the reactor, the fuel bundles are transferred to the New Fuel Transfer Room in the Reactor Building. The fuel bundles, typically eight at a time, are loaded manually into one of the two magazines of the new fuel port.

Transfer of the new fuel bundles into the fuelling machine that is designated to hold the fresh fuel is controlled remotely.

(2) Fuelling Machines

Two fuelling machines, connected to either end of a fuel channel, are needed to change the fuel in a CANDU reactor.

One fuelling machine inserts new fuel bundles into the fuel channel, in the same direction as the flow of coolant in that channel, left to right in this diagram. The irradiated or ‘spent’ fuel bundles are pushed into the other fuelling machine at the downstream end of the fuel channel. Typically either four or more often eight of the 12 fuel bundles in a fuel channel are exchanged during a refuelling operation.

Either of the two fuelling machines can load fresh fuel or receive spent fuel. The direction of loading, and hence the role that each machine will have, depends on the direction of coolant flow in the fuel channel being refuelled, since the flow direction alternates between adjacent channels.

(3) Irradiated Fuel

Following the placement of the irradiated fuel bundles in the fuelling machine the fuel channel is reclosed. The fuelling machine then moves to the Discharge Port, where the fuel bundles are transferred into an elevator, which lowers them into the water filled Discharge Bay.

The irradiated fuel bundles are moved under water through a Transfer Canal into the Reception Bay, where they are loaded onto storage trays or baskets and passed into the Irradiated Fuel Storage Bay.

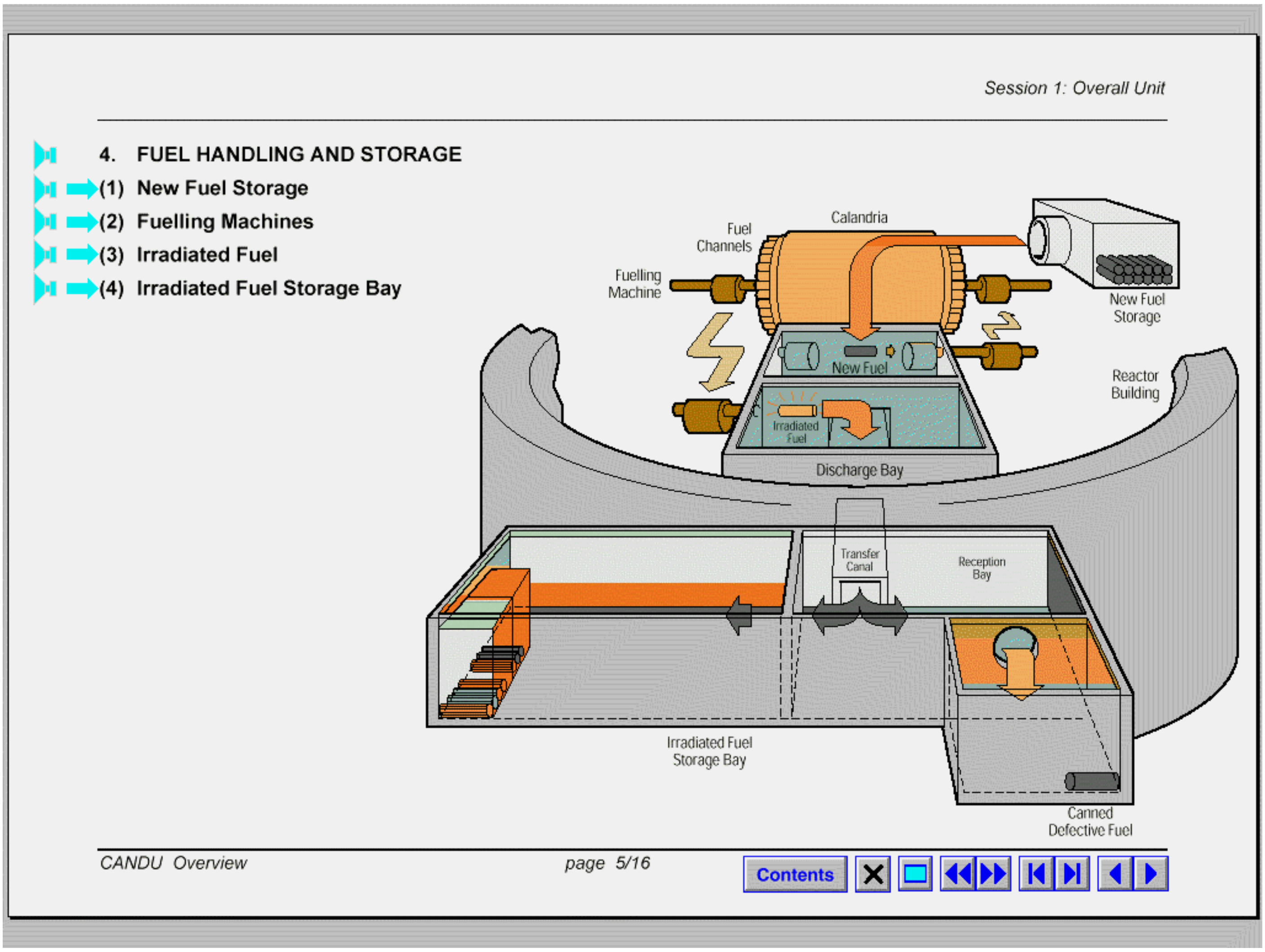
All the transfer operations from the Fuelling Machine to the Irradiated Fuel Storage Bay take place under water, ensuring that the fuel is cooled at all times during removal and transfer, to prevent fuel overheating and possible damage to the bundles.

(4) Irradiated Fuel Storage Bay

Irradiated fuel bundles are stored in the Irradiated Fuel Storage Bay for a minimum of six years before they can be transferred to dry storage. The storage volume of the bays has sufficient capacity of a minimum of 10 years’ accumulation of irradiated fuel. Operations in the Storage Bays are carried out under water, using special tools aided by cranes and hoists.

Defective fuel is placed into protective cans before transfer to the Defective Fuel Bay, in order to limit the spread of contamination.

Because CANDU uses natural uranium fuel, neither the new nor the irradiated fuel can achieve criticality in air or in ordinary light water, regardless of the storage configuration.



5. MODERATOR SYSTEMS

All CANDU reactors use heavy water as the moderator, in a system that is completely separate from the reactor coolant heavy water. About 4% of the reactor thermal power appears in the moderator, due to gamma radiation, the slowing down of fast neutrons, and heat transferred from the fuel channels.

The Moderator Systems consist of the Main Circuit, which circulates the heavy water through the calandria and heat exchangers to remove the heat generated in the moderator during reactor operation.

The operating pressure at the moderator free surface near the top of the Calandria is slightly above atmospheric. A Helium Cover Gas system provides an inert atmosphere at this surface.

Liquid Poisons can be added to the moderator for reactor control and shutdown, and removed via the Purification system.

A Heavy Water Collection system collects any heavy water that leaks from the moderator and associated systems.

(1) The Moderator Main Circuit, removes the heat generated in the moderator during reactor operation and maintains the moderator level in the Calandria. The Calandria is normally full, and the Head Tank is designed to maintain the level within the required range by allowing moderator swell and shrink that result from temperature fluctuations. The pressures and temperatures in the Calandria are kept at slightly above atmospheric conditions.

Two 100% capacity pumps circulate the heavy water moderator through the calandria and two heat exchangers. The moderator heat is rejected to the Recirculated Cooling Water (RCW) System.

The heavy water in the Calandria provides a heat sink in the unlikely event of a loss of coolant accident coincident with failure of emergency core cooling.

(2) A Cover Gas System above the free moderator surface is needed to prevent moisture in the air down-grading the heavy water concentration, and the accumulation of a potentially explosive mixture of deuterium and oxygen gases that result from the radiolysis of the heavy water.

Helium, which is chemically inert and not activated by neutron irradiation, is used as the cover gas. The system controls the concentration of deuterium and oxygen gasses by catalytically recombining them to re-form heavy water.

The Cover Gas System includes two compressors and two recombination units through which the cover gas is circulated.

(3) The Liquid Poison System adds negative reactivity to the moderator when required, such as:

(a) to provide a means of reactivity control by adding dissolved poison to the moderator;

(b) to provide a means of rapid reactor shutdown by injection of poison into the moderator; this is done by Reactor Shutdown System (SDS) #2;

(c) to provide a means of guarantying reactor shutdown by dissolving excess poison into the moderator.

The liquid poisons employed are boron as boric anhydride, and gadolinium as gadolinium nitrate, dissolved in D2O.

(4) The Moderator Purification System has the following main functions:

(a) maintain the purity of heavy water so that the excess production of deuterium and oxygen gases through radiolysis is minimized;

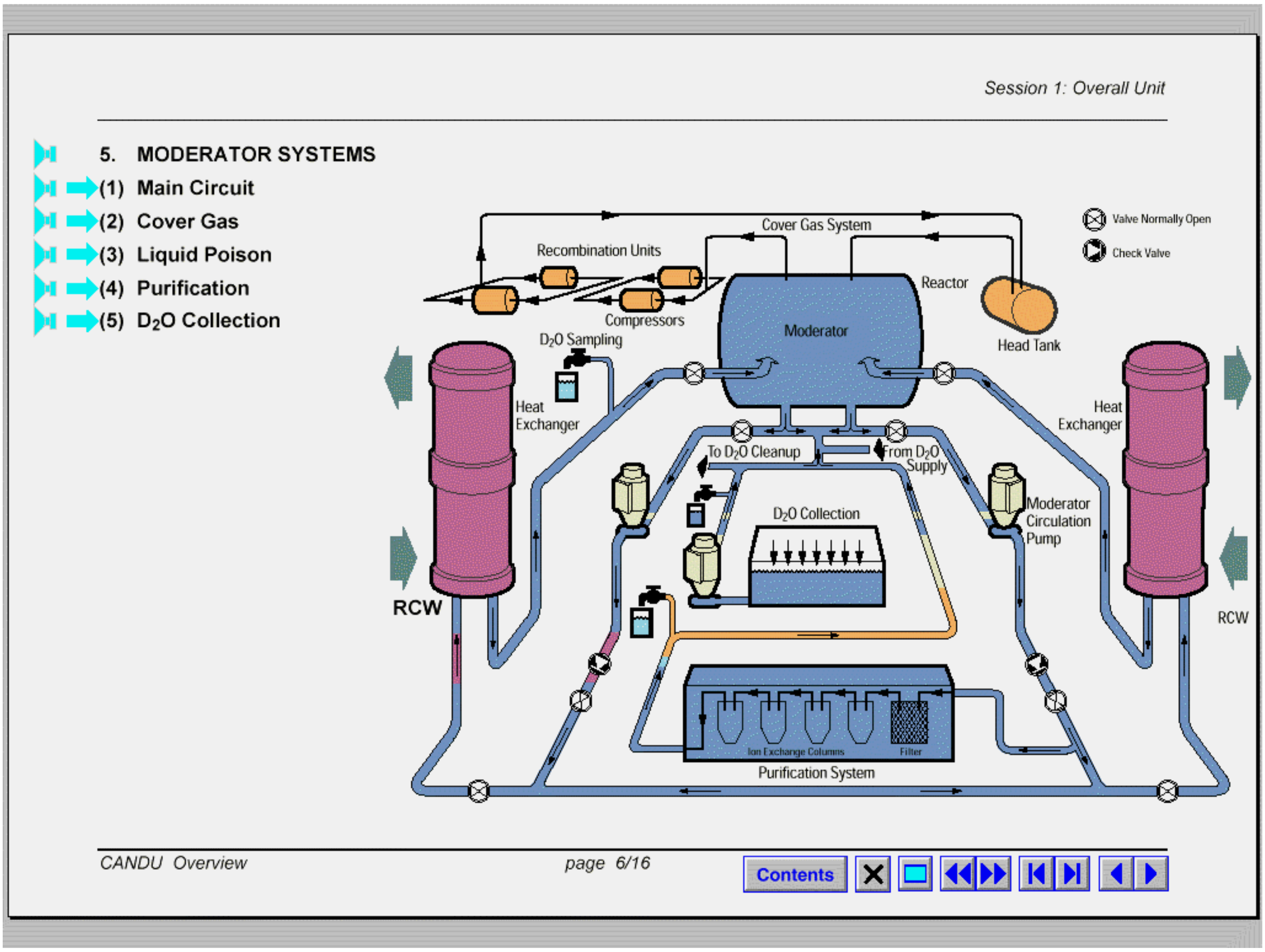
(b) minimize the corrosion of components by removing impurities and controlling the pD level of the heavy water;

(c) control reactivity by reducing the concentration of dissolved poisons boron and gadolinium in the moderator, under the unit operator’s control;

(d) remove the excess gadolinium that was injected in response to a Reactor Shutdown System #2 trip, once the conditions for restarting the unit have been established.

The system consists of a filter and ion exchanger columns.

(5) The Moderator D2O Collection System collects any heavy water leakage from the moderator and associated systems and transfers it into the heavy water management systems for Cleanup and Upgrading.



6. HEAT TRANSPORT SYSTEM

The Heat Transport Main Circuit uses pressurized heavy water to remove the heat produced in the reactor. The heat is carried to the steam generators where it boils the light water on the secondary side to produce steam.

The Heat Transport system must provide for the continuous cooling of the fuel, and it has to contain any fission products that may be released from the fuel.

The Main circuit, as shown on the diagram, consists of two loops, each with a figure of eight coolant flow pattern. Reactor inlet and outlet headers connect the fuel channels through feeder pipes to the rest of the main circuit. There are four steam generators of the vertical U-tube type with an integral preheating section. The four heat transport system pumps are vertical single discharge, electric motor driven, centrifugal pumps with multi-stage mechanical shaft seals.

Under normal operating conditions the Pressurizer maintains the required system pressure.

No chemicals are added to the heat transport system for reactivity control.

(1) Two Loops

The Main Circuit, as shown on the diagram, consists of two loops. Only four representative channels are shown, two per loop, with the coolant flow in opposite directions as the two ‘legs’ of each loop pass through the Reactor. The illustration is indicative of the flow pattern for the actual number of fuel channels, since the coolant flow through the core is bi-directional, i.e. in opposite directions in adjacent fuel channels.

Each loop serves half of the reactor. The fuel channels are divided for this purpose about the vertical centre-plane of the reactor. Having a steam generator and a circulating pump at the ‘ends’ of each loop, the overall effect is a figure of eight coolant flow pattern. The arrows point to the circuit for Loop 1.

(2) The four Steam Generators transfer heat from the reactor coolant, contained on the steam generator primary side, to light water to produce steam on the secondary side. The CANDU 6 and 9 steam generators consist of an inverted vertical U-tube bundle in a cylindrical shell. Steam separating equipment is provided in the steam drum in the upper part of the shell. The steam leaving the steam generator has less than 0.25 percent moisture by weight.

Feedwater enters the baffled preheater section of the steam generator, and flows over the D2O outlet end of the U-tube bundle. Water at saturated temperature from the preheater mixes with recirculating water flowing over the hot leg section of the tube bundle.

(3) The four heat transport Main Circuit Pumps are vertical single discharge, centrifugal pumps with multi-stage mechanical shaft seals. Each pump is driven by a vertical, totally enclosed, air-water cooled squirrel cage induction motor.

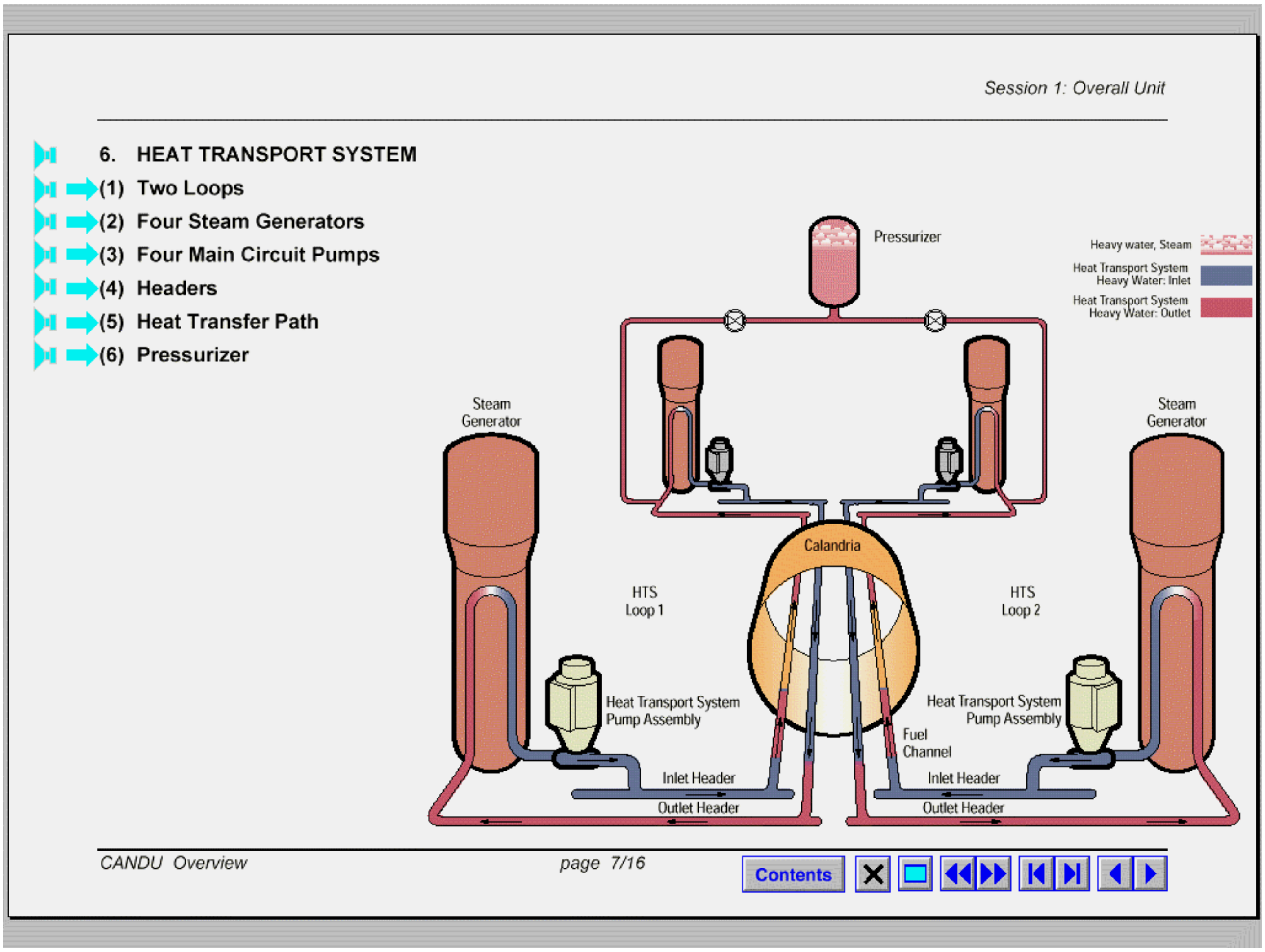
The pump/motor unit has sufficient rotational inertia so that, on loss of motor power, the rate of coolant flow reduction matches the reactor power rundown following reactor trip. Natural circulation maintains fuel cooling after the pumps stop.

(4) Headers

Each pressure tube receives its coolant flow via a feeder pipe connected to a Reactor Inlet Header (RIH), and the coolant leaves the pressure tube via another feeder pipe connected to the Reactor Outlet Header (ROH). In CANDU 6 there are four RIH and four ROH, as shown in the diagram. The CANDU 9 design has combined two of the Inlet Headers, one on either end of the Reactor.

The feeders that connect each fuel channel to the reactor inlet and outlet headers are sized such that the coolant flow to each channel is proportional to channel power. The enthalpy increase of the coolant is therefore the same for each fuel channel assembly.

The operating pressure at the Reactor Outlet Header is 10 MPa. In order to maximize unit thermal efficiency, boiling in the core at high power is permitted, leading to an Reactor Outlet Header steam quality of up to 4% at full power.



(5) Heat Transfer Path

Please refer to the arrow numbers shown on the diagram.

(a) The coolant emerges hot, shown by red colour, from the fuel channels.

(b) All the feeders from a quarter of the fuel channels are connected to the given ROH, from which the hot heavy water flows to the steam generators, where it is transfers heat to the light water on the secondary side.

(c) The once again cooled heavy water enters the Heat Transport Circulating pump, then flows to the RIH.

(d) The RIH distributes the coolant to each of the feeder pipes connected to it, sending the coolant to the inlet of the fuel channels, flowing in the opposite direction from the earlier set.

(e) The coolant is heated once again as it flows past the fuel, and emerges at the other end of the reactor, flowing through the ROH, the Steam Generator, and the Circulating pump.

(f) The loop is completed with the coolant going through the RIH back to the first set of fuel channels.

(6) The Pressurizer maintains the required system pressure under normal operating conditions. The Pressurizer's liquid and steam are kept at saturation, and at a pressure that is slightly higher than the saturation conditions in the reactor outlet header at 100%FP.

Pressurizer and hence heat transport pressure can be raised by adding heat to the liquid via electric heaters, and the pressure can be reduced by bleeding steam out of the pressurizer.

During a reactor power increase the outlet header pressure rises as a result of the swell in the system. The level setpoint in the pressurizer increases automatically so that all the swell resulting from power increases is stored in the pressurizer.

The level in the pressurizer, and hence the heat transport system inventory, is normally controlled via the Heat Transport feed and bleed flows. In cases when the Pressurizer is isolated from the Main Circuit, the feed and bleed flows also control the system pressure.

7. STEAM GENERATOR AND MAIN STEAM SYSTEMS

The Steam Generator and Main Steam Systems include the four Steam Generators, the piping and valves that direct the flow of steam to the Turbine, to other steam loads, or to by-pass these loads when the need arises.

As discussed earlier, the heavy water reactor coolant of the Heat Transport System flows through hundreds of small inverted ‘U’ tube bundles in each of the four Steam Generators (only one shown in the diagram) and transfers heat to the light water supplied by the Feedwater System. The steam from the Steam Generators is fed by separate piping, called Steam Mains to the Turbine Steam Chest via the Turbine Stop Valves, and its flow is controlled by the Governor Valves.

When the turbine cannot accept the full steam flow, the excess steam can be discharged to the atmosphere or bypass the turbine by flowing directly to the condenser.

Over-pressure protection is provided by four Safety Relief Valves on each steam main.

(1) Steam Flow Measurements are made in each of the four Steam Mains, and are used for:

- (a) Input to the Reactor Regulating System for the computation of Reactor Thermal Power .
- (b) Input to the Steam Generator Level Control program to control the opening of the Feedwater valves.
- (c) Display by the Computerized Plant Display System and on the Control Room Panel Instruments.

(2) There is a Main Steam Isolation Valve in each of the four Steam Mains. These are motorized valves that are normally open, and are closed remote-manually only after the reactor had been shut down. They are provided for the purpose of being able to isolate each Steam Generator from the rest of the system, typically in cases that involve leakages from the primary side of the Steam Generators to the secondary side.

(3) There are four Steam Safety Relief Valves (also called Main Steam Safety Valves or MSSV) in each of the four Steam Mains, but only one per line is shown in the diagram. These are spring-loaded valves with auxiliary pneumatic operators. Their combined capacity is such that three out of the four MSSV’s provide a flow of 115% of the steam flow from each steam generator. The valves have staggered set pressures, and will open between 5.11 MPa and 5.24 MPa.

(4) There is an Atmospheric Steam Discharge Valve, in short ASDV, in each of the four Steam Mains. These valves have a total capacity of 10% of the unit’s full power steam flow.

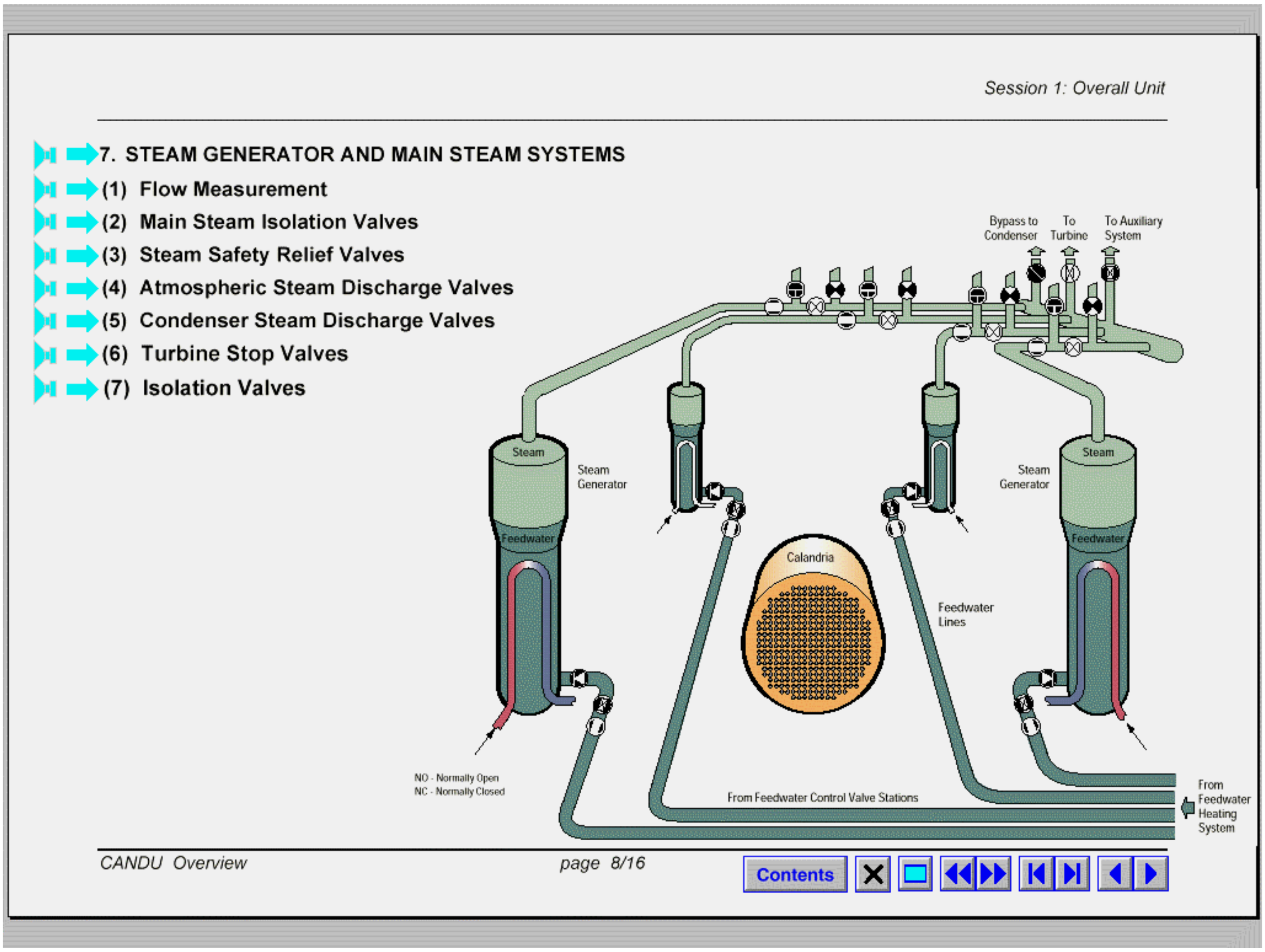
The ASDVs are normally closed, and are controlled by the Steam Generator Pressure Control program. They are opened when the Main Steam Header Pressure rises above the ASDV setpoint, which is typically 70 kPa above the Main Steam Header Setpoint. The valve opening is proportional to the pressure error. The ASDVs are also used to provide a heat sink for the reactor when the main condenser is unavailable.

The ASDVs open fully before the CSDVs begin to open. They are capable to go from closed to fully open in less than 2 seconds.

(5) There are two Condenser Steam Discharge Valves, in short CSDVs connected from the Main Steam Header to the Condenser. Only one of these is shown on the diagram. These valves have a combined capacity of 100% of the unit's full power steam flow in case of a load rejection. The turbine bypass system is sized to permit a continuous steam flow to the condenser of up to 60% of full power steam flow.

The main function of these valves is to bypass the steam to the condenser when the turbine is not available, so that the reactor can continue to operate at up to 60%FP, in order to prevent a poison-out.

The CSDVs are normally closed, and are controlled by the Steam Generator Pressure Control program. They are opened when the Main Steam Header Pressure rises above the CSDV setpoint, which is typically 100 kPa above the Main Steam Header Setpoint. The CSDVs are capable to go from closed to fully open in less than 1 second.



(6) There are Turbine Stop Valves (also called Main Stop Valves) upstream of the turbine control valves. These are hydraulically operated spring-closed valves that are normally open. Their main function is to

close rapidly when required to protect the turbine against over-speed if the turbine control valves fail. Only one of these valves is shown on the diagram.

(7) There is an Isolation Valve in each of the steam lines to the various Auxiliary Systems. These are motorized valves that are normally open, and are closed either by automatic logic or remote-manually from the Main Control Room. They are provided for the purpose of being able to isolate each Auxiliary System from the Main Steam Header, typically in cases that involve leakages from the primary side of the Steam Generators to the secondary side.

8. FEEDWATER SYSTEM

The feedwater system supplies demineralized and preheated light water to the steam generators. The flow to each steam generator is via a set of valves, that include pneumatic control, motorized isolation, and check valves.

Varying the feedwater flow to each Steam Generator controls its level. The level setpoint is varied as a function of reactor power to ensure a consistent inventory of water in the steam generators, despite the expansion of the water with increased boiling.

The actual level measurement is combined with measurements of steam and feedwater flow, and the resultant control signal is used to adjust the feedwater control valve opening.

(1) Feedwater Flow Measurements are made in each of the four Feedwater Lines. These measurements are used for:

(a) Input to the Reactor Regulating System for the computation of Reactor Thermal Power .

(b) Input to the Steam Generator Level Control program to control the opening of the Feedwater valves.

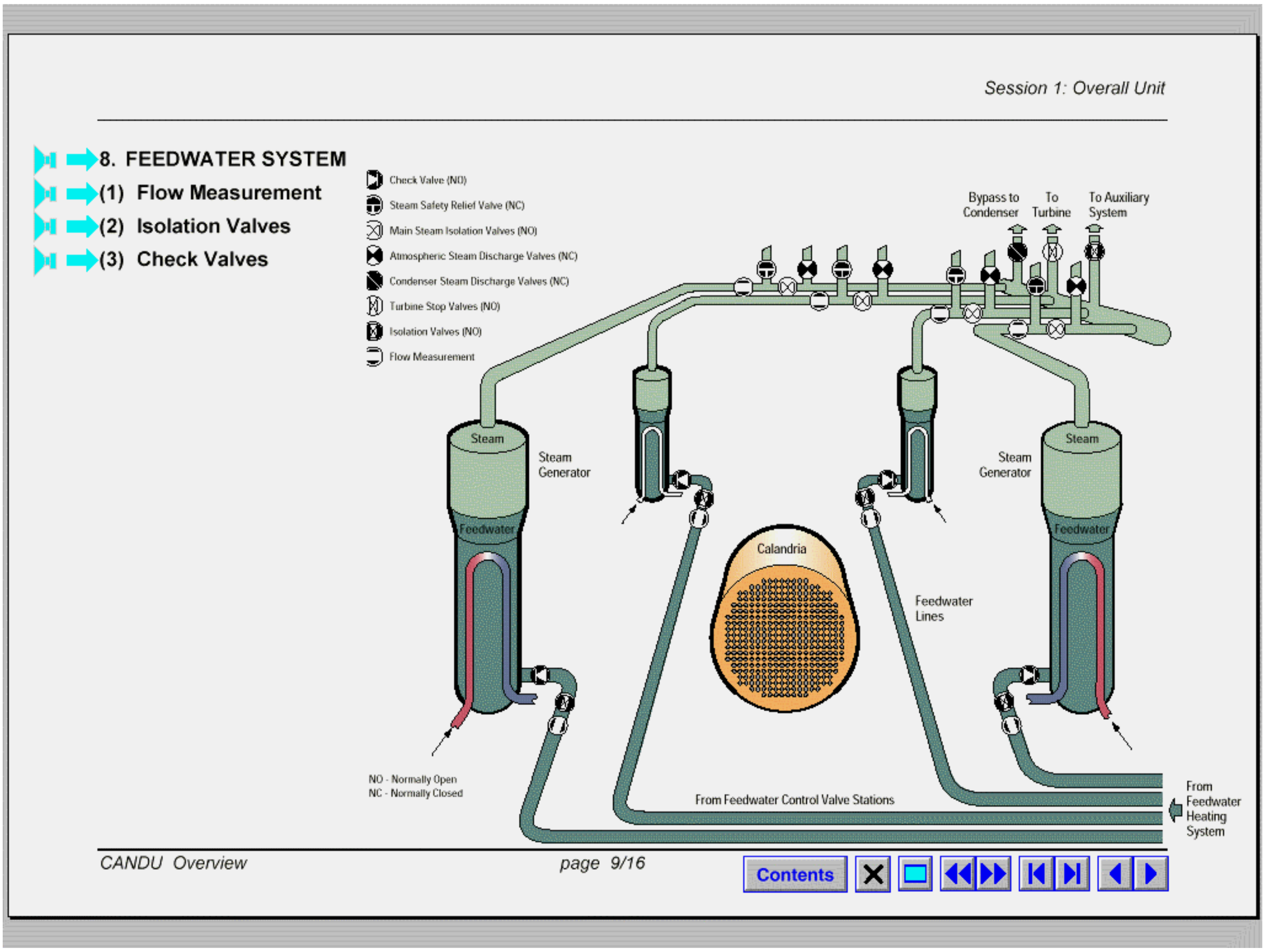
(c) Display by the Computerized Plant Display System and on the Control Room Panel Instruments.

(2) The Isolation Valves drawn in each of the Feedwater lines on the diagram are in fact a set of six valves, consisting of three parallel lines, each having a Control Valve and an Isolation Valve in series, as shown in the red line diagram.

The Isolation Valves are motor driven and are normally open. They are closed either by automatic logic or remote-manually from the Main Control Room. They are provided for the purpose of being able to isolate each Feedwater Flow Control Valve, typically in cases when the associated control valve needs to be removed from the flow path.

(3) There is a Check Valve, also called non-return valve, in the Feedwater line upstream of the flow entering each Steam Generator.

These valves are provided to prevent backflow in the unlikely event of feedwater pipe failure.



9. TURBINE, GENERATOR, CONDENSATE AND FEEDHEATING SYSTEMS

The diagram shows the main systems involved in converting the heat energy of the steam in the turbine to rotational energy, which in turn drives the generator to convert the mechanical energy to electrical energy.

In order to extract maximum energy from the steam, it needs to be condensed to a pressure and temperature that is as low as practicable. This takes place in the condenser, with the heat being removed to the environment by the condenser cooling water.

The feedheating system uses extraction steam from the turbine to raise the temperature of the feedwater before returning it to the steam generator. The flows, temperatures and pressures of the steam and feedheating systems are designed to optimize the thermodynamic efficiency of the steam cycle.

The following items highlight each of the main components in the turbine, generator and feedheating systems.

(1) The Main Steam Header collects the steam flow from the individual steam mains coming from each of the four steam generators, and distributes the steam to various loads.

Under normal operating conditions most of the flow is via the Governor Valves to the high pressure turbine. Smaller amounts go to the Steam Reheater, the high pressure heaters and some auxiliary loads.

If the Steam Generator Pressure rises above predetermined setpoints, usually because the turbine is unable to accept the full steam flow, steam release valves to the atmosphere and to the condenser open to discharge the excess steam, and to control steam pressure at its setpoint.

The diagram shows the Steam Mains, the steam flow to the Steam Reheater, the Governor Valve and the Condenser Steam Discharge Valves.

(2) The High Pressure Turbine is a double-flow unit, designed to work with saturated inlet steam. The amount of steam flowing to the high pressure turbine is controlled by the Governor Valves. Emergency Stop Valves in series with the Governor Valves are fully open under normal operating conditions, but will close rapidly in the even of a turbine trip.

(3) Separator and Reheater.

Steam exiting the high pressure turbine has about 10% moisture content, which must be removed prior to admitting the steam to the low pressure stages.

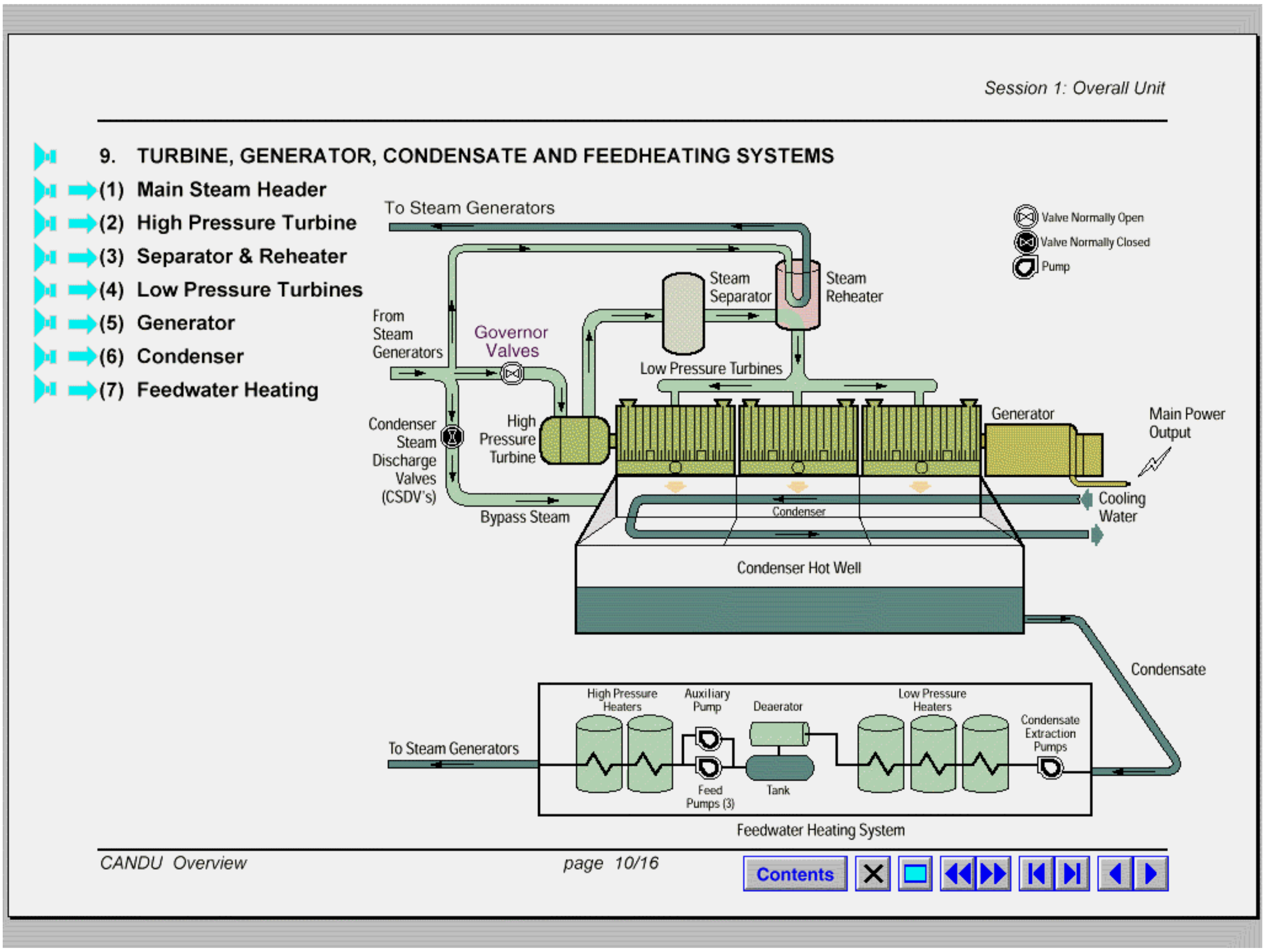
The Separator uses mechanical means to remove much of the moisture content, and in the Reheater live steam raises the steam to superheated conditions.

(4) The Low Pressure Turbine stage consists of three double flow low pressure cylinders. The steam from the Reheater passes through a set of intercept and release valves which, in the case of a turbine trip, will stop the flow of steam to the low pressure cylinders (intercept valves close) and bypass the steam to the condensers (release valves open).

Each of the three low pressure turbine cylinders is connected to a separate condenser shell where the exhaust steam is condensed.

(5) The Generator is a three-phase four-pole machine directly coupled to the turbine. In the case of electrical system operating at 50 Hz, the generator typically operates at 1800 rpm, and for 50 Hz systems at 1500 rpm. The output voltage is typically 24,000 volts, and is connected via forced air cooled, isolated phase bus duct to the step-up Main Output Transformer.

Cooling of the rotor winding and stator core is by hydrogen, and of the stator winding by water.



(6) The Condenser consists of three separate shells, one for each low pressure turbine cylinder. The exhaust steam from each turbine cylinder flows into the shells where it is condensed by flowing over tube bundle assemblies through which cooling water is pumped.

The condensed steam collects in the bottom of the condenser, in what is called the "hot well". The condenser is capable of handling 100% steam flow for a few minutes, to allow reactor power to be reduced to 70% full power or lower, and at these levels the condenser can accept by-pass steam flow continously.

(7) The Feedwater Heating System uses extraction steam to preheat the feedwater in order to optimize thermodynamic efficiency and to raise the temperature of the feedwater to the desired value for admission to the steam generators.

The main components of the Feedheating System are shown on the diagram. Starting from the Condenser Hot Well, the condensate is pumped through three low pressure heater units. In the Deaerator dissolved oxygen and other non-condensable gases are removed. The associated Storage tank acts as a reserve of feedwater, and by locating it high in the turbine building, it also provides the net positive suction head to the main feedwater pumps. Typically three large feed pumps and one auxiliary pump are used to return the feedwater to the steam generators.

Two high pressure heaters raise the temperature of the feedwater to a sufficient level to minimize thermal shock when entering the preheater section of the steam generator, where the feedwater temperature is raised to saturation value.

10. REACTOR SHUTDOWN SYSTEMS (SDS#1 and SDS#2)

In this and the next two sections we take a brief look at what are called the Special Safety Systems. These systems do not take any part in normal power plant operations, but are "poised" to act. In other words, they are waiting and watching in case the processes and their control systems cannot keep key operating parameters within prescribed limits. In such cases, when there is the potential for fuel failure to occur with a risk of radioactivity release, these special safety systems spring into action. If the control of reactor power is not assured, one or both Reactor Shutdown Systems will shut it down. If cooling of the fuel is judged to be insufficient, Emergency Core Cooling will be implemented; and if there is a risk, or perhaps an actual release of radioactivity from any of the plant systems, then the Containment System will ensure that no unsafe level of radiation is released to areas outside the plant's boundary.

(1) There are two 'full capability' reactor shutdown systems in CANDU units. They are called Shutdown System Number 1, in short SDS1, and Shutdown System Number 2, or SDS2.

These two reactor shutdown systems are functionally and physically independent of each other, and each is able, on its own, to shut down the reactor and to keep it in the shutdown state.

As shown in the diagram, SDS1 uses solid neutron absorbing rods that are dropped into the core, while a liquid poison is injected into the moderator for SDS2. There is a very high level of functional independence provided by using two such fundamentally different methods of shutdown.

There is also a large measure of physical independence between systems as a result of the shutdown rods having been positioned vertically through the top of the reactor, while the poison injection tubes are located horizontally through the sides of the reactor.

The desired very high level of independence is further enhanced by using diversity between the two shutdown systems in every possible area, such as the types of instruments used, the choice of trip parameters, the type and source of control equipment hardware, the software languages used, and even the membership of the design and analysis teams.

(2) Shutdown System Number 1 is the primary method of quickly shutting down the reactor. SDS1 employs instruments that give parameter measurements and logic systems that process these measurements, that are different and independent from the corresponding components of SDS2 and the reactor regulating system. When the conditions for a reactor trip are detected by the SDS1 circuits, they send signals to de-energize the clutches that hold the neutron absorbing shutdown rods in their poised positions above the reactor core, allowing them to fall into the core.

The design philosophy of the trip systems is based on triplicating the measurement and processing of each signal, and initiating their protective action when any two of the three channels indicate that a trip condition exists based on any one variable, or a combination of different variables.

(3) Shutdown System Number 2 uses the rapid injection into the Moderator of a liquid that contains a strong neutron absorbing substance, for CANDU this is concentrated gadolinium nitrate. Such a liquid is called a "poison" because it rapidly shuts down the nuclear chain reaction.

The liquid poison is held in tanks outside the reactor, and the gas spaces above the liquid poison tanks are connected by a highly reliable set of quick opening valves to a tank containing helium under a high pressure. The triplicated parameter sensors and logic circuits of SDS2 are fully independent of the equipment and circuits of SDS1 and of the reactor control system, as I pointed out earlier. When the SDS2 logic system determines that there is a requirement for it to shut down the reactor, the fast-acting valves are opened, and the high pressure helium expels the liquid poison from the tanks into the horizontal tubes that are installed through the side of the calandria and through the injection nozzles into the moderator heavy water.

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10. REACTOR SHUTDOWN SYSTEMS (SDS#1 and SDS#2)

(1) There are two 'full capability' reactor shutdown systems, called Shutdown System Number One (SDS#1) and Shutdown System Number Two (SDS#2). They are functionally and physically independent of each other, and each able to shut down the reactor;

(2) SDS#1 drops solid neutron absorbing rods into the core and these shutoff units are installed vertically through the top of the reactor.

(3) SDS#2 injects liquid poison into the moderator and the poison injection tubes are installed horizontally through the sides of the reactor.

(4) The two shutdown systems respond automatically to both neutronic and process signals

(5) a very high level of independence is achieved by using diversity in:

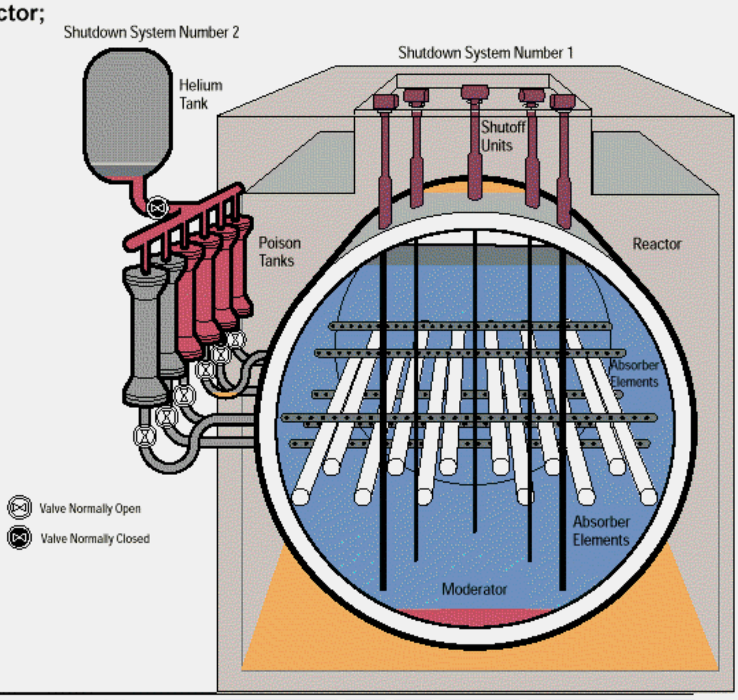
(a) the types of instruments used,

(b) parameters measured

(c) the control equipment hardware

(d) software language

(e) design and analysis teams.



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(4) Both SDS1 and SDS2 respond automatically to carefully chosen parameters, which include neutronic as well as process system signals. In addition to choosing as many different parameters to be measured as possible, if the same or similar trip parameter is used than the type of instrument, and its electrical supply will be different.

Typical variables that are used as trip parameters include the following:

- high neutron power
- high rate of log neutron power
- low heat transport coolant flow
- high heat transport pressure
- low pressurizer level
- low steam generator level
- high containment building pressure

(5) The desired very high level of independence between SDS1, SDS2 and the reactor regulating system is further enhanced by using diversity between these systems in every possible area, such as the types of instruments used, the source of electric and pneumatic power, the location and spatial orientation of wire runs, the choice of trip parameters, the type and source of control equipment hardware, the software languages used, and even the membership of the design and analysis teams.

11. NUCLEAR POWER PLANT SIMPLIFIED SCHEMATIC

This diagram shows a simplified schematic or block diagram of a typical nuclear power plant such as CANDU.

In order to help to explain how the control systems maintain the energy balance and do their control functions, I have broken down the diagram into five main groups of systems, namely the Nuclear Steam Supply Process Systems, the Steam Utilization Process Systems, the Nuclear Steam Supply Control Systems, the Steam Utilization Control Systems, and the Special Shutdown Systems.

By selecting each of these five topics we can build up the schematic diagram in a step-by-step fashion.

(1) Nuclear Steam Supply Process Systems

On this very much simplified diagram, I used only two blocks and the interconnecting circuit to represent the Nuclear Steam Supply Process Systems.

The Reactor block, the principle source of energy for the power plant, is indicated to include the nuclear fuel, the reactor coolant and the moderator.

The Steam Generator block is where the transfer of energy from the heavy water reactor coolant on the primary side to the light water on the secondary side of the steam generator takes place.

The Heat Transport system is shown only as the interconnection between the reactor and the steam generator blocks, with the pump symbol indicating the flow of coolant around the circuit, transferring heat from the reactor to the steam generator.

As we will see, from an overall unit control point of view, these three process systems of the Nuclear Steam Supply side of the plant are the ones of principle interest.

(2) For the <u>Steam Utilization Process Systems</u> I have chosen to highlight two groups of systems.

In the upper part of the diagram are the High and Low Pressure Turbines, with the Moisture Separator and Reheater between them, and the condenser at the outlet of the low pressure stage. The generator is connected to the same shaft as the turbine. As we will see, these are the systems principally involved with unit electrical output control and steam generator pressure control.

The lower part of the diagram shows the main blocks of the feedheating system, including the Condensate Extraction pumps, Low and High Pressure Heaters, the Deaerator and the Feedwater pumps. We will see how steam generator level control is accomplished in connection with the feedwater system.

(3) The two <u>Nuclear Steam Supply Control Systems</u> that we need to consider at this stage are the Reactor Regulating System and the Heat Transport Pressure and Inventory Control System.

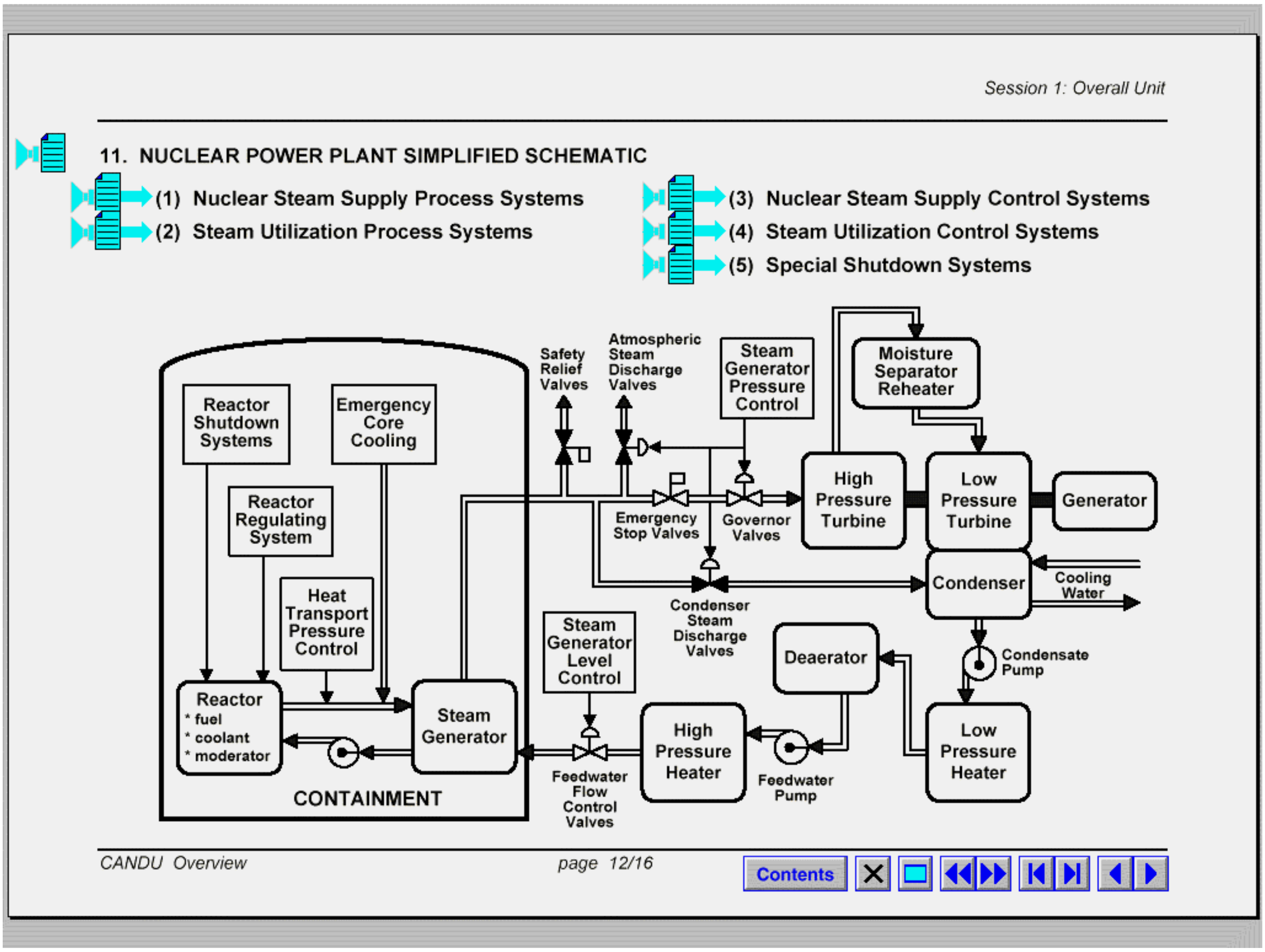
The Reactor Regulating System has the task of keeping reactor power at the required level, and to maneuver it from one level to another at specified rates.

The Heat Transport Pressure Control System maintains the high pressure required to keep the coolant in the liquid state. During power operations, the pressure is constant, it only changes when the unit is not producing electric power and the reactor is in a shutdown state.

Because of thermal expansion, the volume of heavy water in the main circuit changes as a function of operating temperature, so control of the heavy water inventory is an integral part of the Heat Transport Pressure Control System.

(4) The two Steam Utilization Control Systems that we will deal with in this course are the Steam Generator Pressure Control System and the Steam Generator Level Control System.

The valves connected to the steam line from the steam generator to the turbine are involved in steam generator pressure control and protection. Under normal operating conditions the steam flow is from the steam generator through the Emergency Stop Valves that are fully open, and through the Governor Valves. The openings of the Governor Valves alter the amount of steam that flows to the turbine, and hence the power produced by the turbine. Changes in steam flow also affect the steam generator pressure.



If the pressure rises above a specified margin, the Atmospheric Steam Discharge Valves open to limit the rise in steam pressure. If the pressure increases further, the Condenser Steam Discharge Valves open to bypass the turbine and discharge the steam directly to the condenser.

In case the Atmospheric and Condenser Steam Discharge Valves cannot maintain steam pressure below a specified value, the Safety Relief Valves open to ensure that the steam pressure does not exceed the safety limit.

Steam Generator Level Control is achieved by altering the openings of the Feedwater Flow Control Valves. By increasing the valves' openings, the flow of feedwater and hence steam generator level will increase, while the converse takes place if the valves' openings are decreased.

(5) Special Shutdown Systems.

All the systems that we have discussed so far have various safety devices and operating limits as integral parts of the design of each system. In nuclear power plants, there are additional safety features, and in particular special safety systems, that are designed to prevent the reactor's power level from going too high, ensuring that there is cooling of the fuel at all times, and that any radioactivity that may be inadvertently released from the fuel or any other station system, is contained within the reactor building structure.

In CANDU plants, there are two independent Reactor Shutdown Systems, each of which is fully capable to shut down the reactor and to keep it in the shutdown state.

The Emergency Core Cooling System has a high pressure injection part, an intermediate pressure injection component, and equipment for low pressure recovery operation.

The Containment system is designed to withstand the largest expected pressure increase, and to ensure that no unsafe amounts of radiation are released to the public under either normal or accident conditions.

12. CANDU NORMAL AND ALTERNATE MODES OF UNIT CONTROL

In this section we look at how the overall unit control modes are realized for CANDU power plants.

There are two basic alternatives, but one of these has two variants.

First we have "NORMAL" mode, in which the turbine leads the reactor.

The second case is "ALTERNATE" mode, in which the reactor leads the turbine, and the turbine is under Steam Generator Pressure Control.

We distinguish a third case, when the reactor is in "ALTERNATE" mode, but the turbine is Manually controlled. This mode is only used during certain stages of start-up and shutdown.

(1) In NORMAL mode, the unit operator specifies the target value of generator output setpoint and its rate of change.

The Unit Power Regulator uses the target values to change the generator power setpoint from its existing value to the new value. It also compares the setpoint with the actual generator output power, and in case of a difference sends a signal to the Turbine Controller, requesting a corrective action. The Turbine Controller will adjust the Governor valves to eliminate the error.

The Steam Generator Pressure Controller continuously monitors steam generator pressure. In response to a pressure error, it calculates a change in the reactor power setpoint, and sends the change request to the Reactor Regulating System.

The Reactor Regulating System computes a new setpoint based on the request from the Steam Generator Pressure Controller. It also compares the actual Reactor Power with the demanded power setpoint, and makes changes to the reactivity mechanisms so as to eliminate the reactor power error.

Changes in reactor power will result in changes in the heat generated in the reactor and through the actions of the heat transport system, to the amount of heat transferred to the steam generators. As the amounts of heat given up in the steam generators change, there will be corresponding changes in steam generator pressure.

If the steam pressure rises above a predetermined level, the Steam Generator Pressure Controller will open the ASDVs, and if there is a further increase in pressure, the CSDVs also.

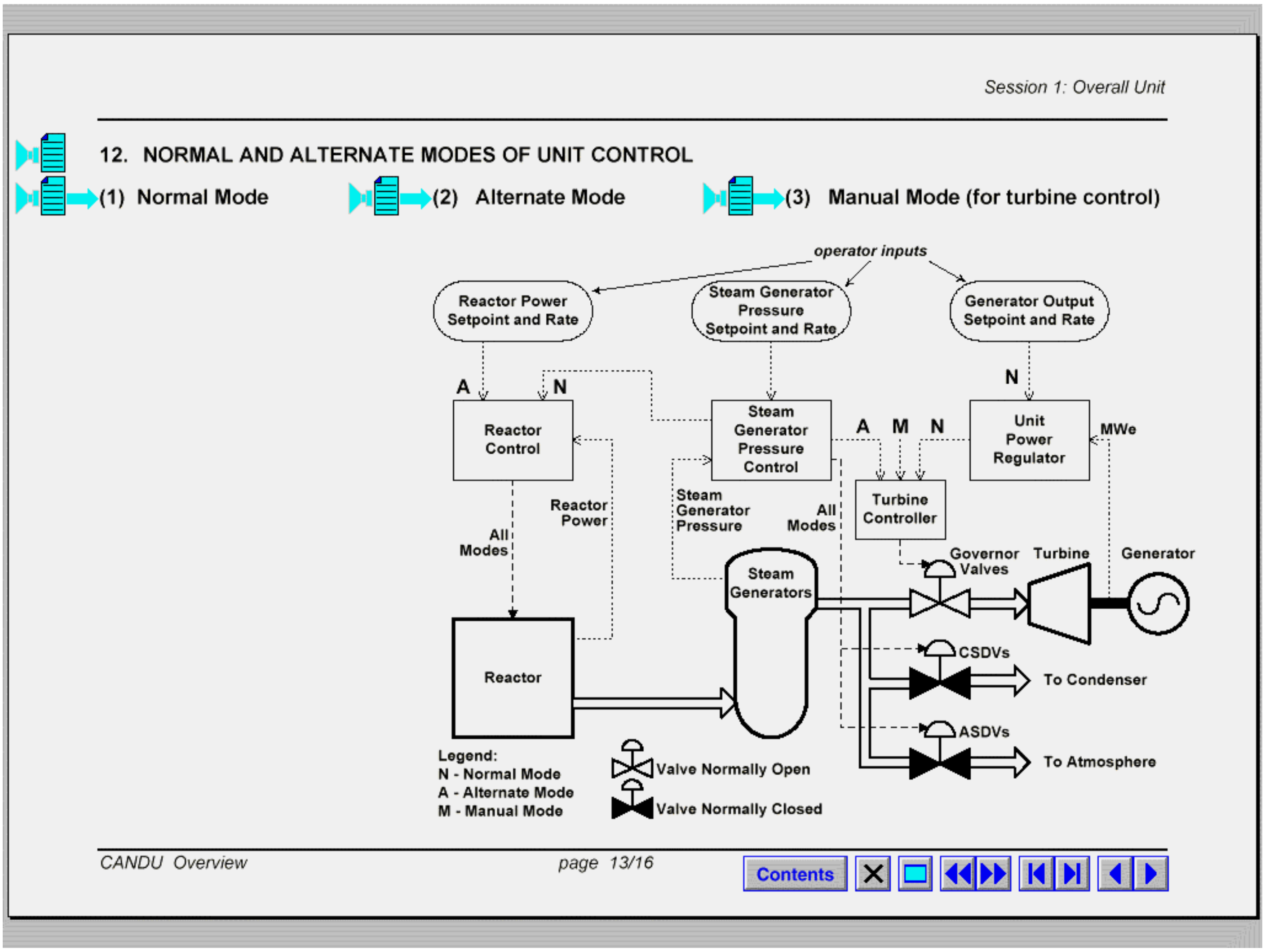
(2) In ALTERNATE mode, the unit operator specifies the target value of reactor power setpoint and its rate of change.

The Reactor Regulating System uses the target values to change the reactor power setpoint from its existing value to the new value. It also compares the setpoint with the actual reactor power, and makes changes to the reactivity mechanisms so as to eliminate the reactor power error.

Changes in reactor power will result in changes in the heat generated in the reactor and through the actions of the heat transport system, to the amount of heat transferred to the steam generators. As the amounts of heat given up in the steam generators change, there will be corresponding changes in steam generator pressure.

The Steam Generator Pressure Controller continuously monitors steam generator pressure, and compares it with the setpoint, which is constant, except under certain startup and shutdown conditions. In case of a pressure error, it sends a signal to the Turbine Controller, requesting a corrective action. The Turbine Controller will adjust the Governor valves to eliminate the error.

If the steam pressure rises above a predetermined level, the Steam Generator Pressure Controller will open the ASDVs, and if there is a further increase in pressure, the CSDVs also.



(3) The Turbine Controller may be disconnected from the steam generator and placed under MANUAL control under certain startup and shutdown conditions. The reactor will be in ALTERNATE mode in such a case, as described in item (2).

The Steam Generator Pressure Controller has no effect on the Governor valves in this mode of operation. The only control action it has is to open the steam discharge valves in case the steam pressure rises above the setpoints for the ASDVs and CSDVs.

13. SIMPLIFIED BLOCK DIAGRAM OF THE MAIN PROCESS AND CONTROL SYSTEMS

In Section 8 we extend what we have learned in the previous four sections about overall unit control. We will look at how the systems involved in overall unit control interact with the main process systems under normal operating conditions. We also will take a brief look at two other control systems that are not directly involved in Overall Unit Control, but which do have important control actions in maintaining heat transport pressure and inventory, and steam generator level at the correct values. I will use this simplified block diagram to illustrate each of six important areas of CANDU process and control systems.

(1) The first set of blocks I would like to consider are the Reactor, the Moderator and the Reactor Regulating System. The main interactions are shown on the diagram, and they include:

- fresh fuel being added to the reactor and spent fuel being removed,

- the flow of heat transport heavy water that removes the heat generated by the reactor,

- the flow of moderator heavy water to and from the reactor, removing the heat generated in the calandria heavy water and other structures,

- the Reactor Regulating System, which measures the power level in the reactor, compares it with the operator specified setpoint, and makes adjustments to the reactivity mechanisms to eliminate any error between the actual and demanded reactor power levels.

(2) The second set of blocks includes the Main Heat Transport System and the Heat Transport Pressure and Inventory Control System. The main interactions are shown on the diagram, and they include:

- the flow of heat transport heavy water that removes the heat generated by the reactor and transfers it to the Steam Generators,

- the Heat Transport Pressure and Inventory Control System, which is responsible for maintaining a pressure of 10 - 11 Mega Pascals in the main circuit. The pressure in the main circuit is kept at a constant value, irrespective of power level, but because the volume of heavy water in the main circuit varies as a function of the operating temperature, the inventory control system adds or removes liquid as needed from the main circuit.

(3) The third set of blocks includes the Steam Generator and Main Steam System, the Feedwater System, and the Steam Generator Pressure and Level Control Systems. The main interactions are shown on the diagram, and they include:

- the flow of heat transport heavy water that transfers the heat generated by the reactor to the Steam Generators;

- the flow of steam from the Steam Generators to the Turbine;

- the flow of condensed steam from the Turbine via the Condenser and the Feedwater System back to the Steam Generators;

- the Steam Generator Pressure Control System, which is responsible for maintaining a pressure in the order of 4.7 Mega Pascals in the steam generators. The pressure is kept at a constant value irrespective of power level. In NORMAL mode, the pressure control system alters the reactor power setpoint to eliminate any pressure error. In ALTERNATE mode the position of the governor valves is altered to keep steam generator pressure constant;

- the Steam Generator Level Control System adjusts the Feedwater flow in response to changes of inventory of light water in the steam generators: volumetric changes due to temperature differences, variations in steam or feedwater flow, and level fluctuations are all taken into account by the Steam Generator Level Control System.

(4) The forth set of blocks includes the Turbine and Generator, the Turbine Controller and the Unit Power Regulator Systems. The main interactions are shown on the diagram, and they include:

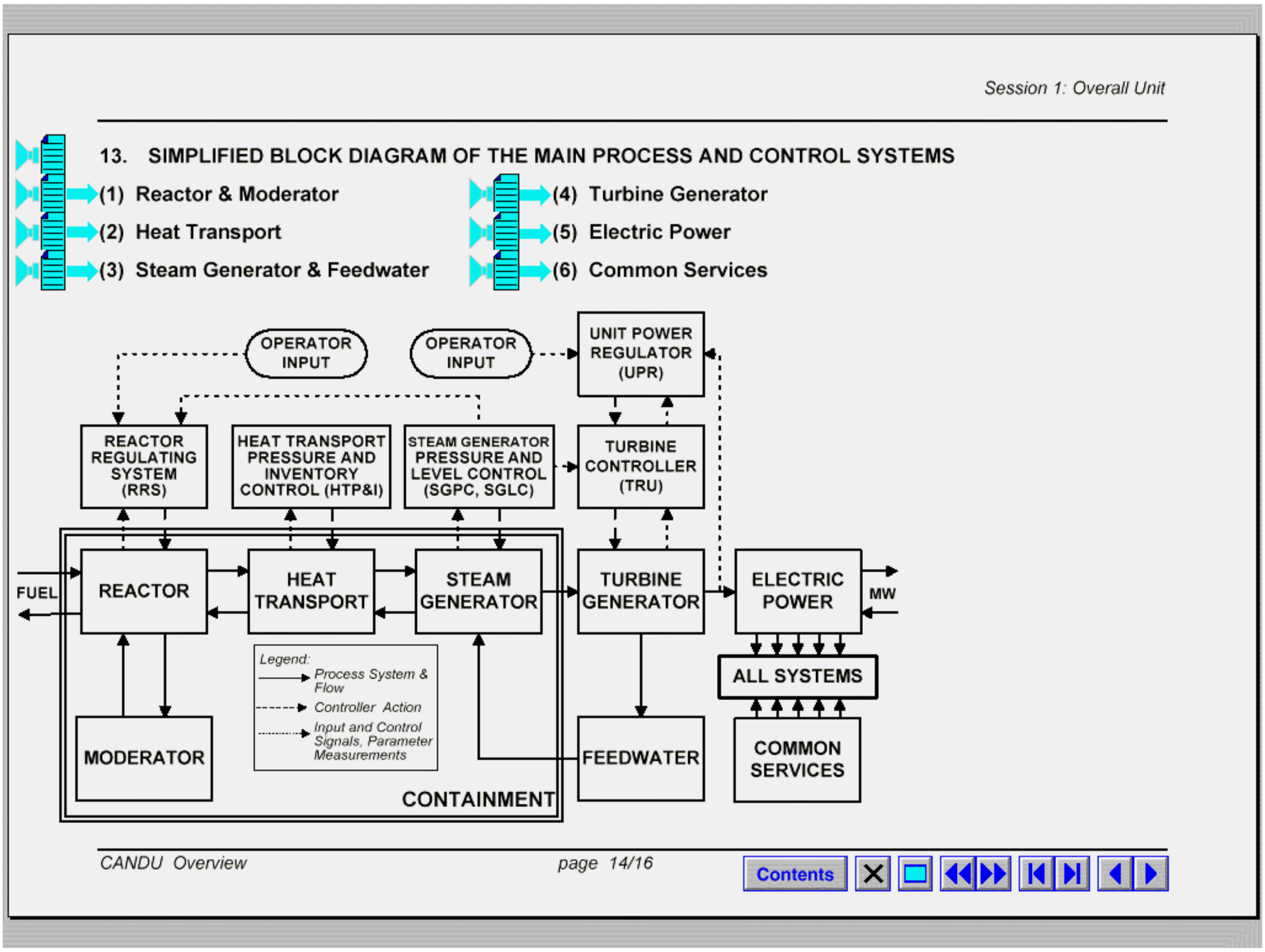
- the flow of steam from the Steam Generators to the Turbine;

- the flow of condensed steam from the Turbine via the Condenser to the Feedwater System;

- the output of electrical energy from the Generator to the Electric Power System;

- the monitoring of Turbine and Generator parameters by the Turbine Control System, and the sending of control signals from the Turbine Controller to the Governor Valves, Emergency Stop Valves, Atmospheric and Condenser Steam Discharge Valves;

- the Unit Power Regulator System, which receives the demanded generator power level from the operator, compares it with the actual generator output, and subject to the status of the Turbine parameters, instructs the Turbine Controller to make the necessary adjustment in valve openings to match the actual and demanded generator power levels.



(5) The fifth topic to be considered on the block diagram is the Electric Power System. It includes the Electric Output System and Plant Electrical Distribution System. The main interactions are shown on the diagram, and they include:

- the flow of electrical energy from the Generator to the Bulk Electric Power System, which is often simply called the Grid;

- the output of the generated electrical energy, after transformation, to the Grid;

- the flow of electrical energy from the Grid, after transformation, to the plant systems;

- and it is important to note, that as shown on the diagram, all the plant systems receive electrical energy at various voltages from the Plant Electrical Distribution System.

(6) The sixth topic to be considered on the block diagram is called Common Services. It includes all the water and pneumatic systems, communication systems, chemical and waste handling, transportation of materials and equipment, and many others. These are far too numerous to cover in this course, but as indicated in the diagram, Common Services, in one form or another, interact with all the systems that constitute an operating nuclear generating station.

14. COMPUTERIZED PLANT CONTROL SYSTEMS

So far in this Session we have looked at various aspects of overall unit control. In this section I have summarized some key aspects of the five main CANDU process control systems. As noted earlier, the control algorithms for each of these systems is implemented in the form of software, executed on both of a unit's Digital Control Computers. In the table I have listed for each program the parameters being measured, the variables that are controlled, and the variables that are manipulated by the control system.

(1) The Unit Power Regulator or in short form UPR program has as input the measurement of electrical output from the unit, which is compared with the setpoint for unit power output. The variable that is controlled is the electrical output of the generator, and this is accomplished by varying the steam flow into the turbine by altering the opening of the governor valves.

(2) The Reactor Regulating System or in short form RRS program has as inputs various measurements of reactor neutron power, both for the reactor as a whole and its spatial distribution, as well as measurements that indicate the thermal power being produced by the reactor. The total reactor neutron power is compared with the reactor power setpoint to compute the reactor power error. The variable controlled is the neutron flux, by altering the positions of the various reactivity mechanisms, such as the insertion or removal of control rods, and the level of water in the liquid zone controllers.

(3) The Heat Transport Pressure and Inventory Control System or is short form HTP&I program has as input Reactor Outlet Header (ROH) Pressure. This pressure is controlled relative to the pressure setpoint that is constant during normal power operations. ROH Pressure is controlled via the pressure of the Pressurizer, and the inventory of heavy water in the Main Heat Transport circuit is controlled via the level of the Pressurizer. The variables manipulated are the Pressurizer steam bleed valves and the heaters, to control Pressurizer pressure, and the feed and bleed of heavy water to and from the main circuit are used to control Pressurizer level.

(4) The Steam Generator Pressure Control System or is short form SGPC program has as inputs Steam Generator Pressure and Reactor Power. This pressure is controlled relative to the pressure setpoint that is constant during normal power operations. Steam Generator Pressure is controlled in NORMAL mode by altering the Reactor Power setpoint, and in ALTERNATE mode by altering the steam flow through the Governor valves. In case of high pressure, SGPC will open steam discharge valves to the atmosphere and to the condenser.

(5) The Steam Generator Level Control System or is short form SGLC program has as inputs Steam Generator Level, Reactor Power, Steam flow and Feedwater flow. The variable controlled is level, but in a manner that ensures that the inventory of light water in the steam generators is constant at all power levels. Steam Generator Level is controlled by altering the feedwater flow, by changing the opening of the feedwater control valves.

14. COMPUTERIZED PLANT CONTROL SYSTEMS

Because of the complex interdependence of control systems in a CANDU unit, Digital Control Computers (DCC) perform all major control functions. The five main programs with the parameters measured and the different variables controlled and manipulated, are summarized in Table 1.

Table 1: Main CANDU Control Programs.

Program Name	Measured Parameter (s)	Variable(s) Controlled	Variable(s) Manipulated
1. Unit Power Regulator (UPR)	• Electrical output	• Electrical output	• Steam flow
2. Reactor Regulating System (RRS)	• Reactor neutron power • Reactor thermal power	• Neutron flux	• reactivity mechanisms - control rod position - zone water level
3. Heat Transport Pressure and Inventory Control (HTP&I)	• Reactor Outlet Header pressure	• Pressurizer pressure • Pressurizer level	• Pressurizer steam bleed & heaters • D_2O feed & bleed
4. Steam Generator Pressure Control (SGPC)	• Steam Generator pressure • Reactor power	• Steam Generator pressure	• Reactor setpoint • Steam flow
5. Steam Generator Level Control (BLC)	• Steam Generator level • Reactor power • Feedwater flow • Steam flow	• Steam Generator Level (inventory)	• Feedwater flow

15. CANDU 9 OPERATING CHARACTERISTICS

The diagram shows the changes in the main unit parameters as reactor power and generator output are reduced from the normal operating value of 100% full power to zero output. The parameter changes illustrated are essentially the same whether the unit is operating in "NORMAL" or "ALTERNATE" mode, only the magnitude, direction and relative timing of the short term parameter transients would differ.

In "NORMAL MODE" generator power decreases in response to the power level reduction request input via the UPR program, and reactor power follows the decrease. In "ALTERNATE MODE" reactor power decreases in response to the power level reduction request input via the RRS program, and generator power follows.

The other plant parameters are held either constant by their respective control systems, or change in response to programmed setpoint changes, or as consequence of the reduced operating power level.

Heat Transport Pressure is kept constant at 10 MPa by the HT pressure control system.

Heat Transport Flow is kept constant by the mail circulating pump flow characteristics.

The Heat Transport Coolant Temperature change across the reactor slightly increases when power is reduced below 100%FP because reactor inlet temperature drops as power is reduced while the reactor outlet temperature remains essentially constant while there is boiling near the outlet of most channels. Once the outlet channel temperatures fall below the saturation temperature, the coolant temperature change across the reactor also falls as a function of decreasing reactor power.

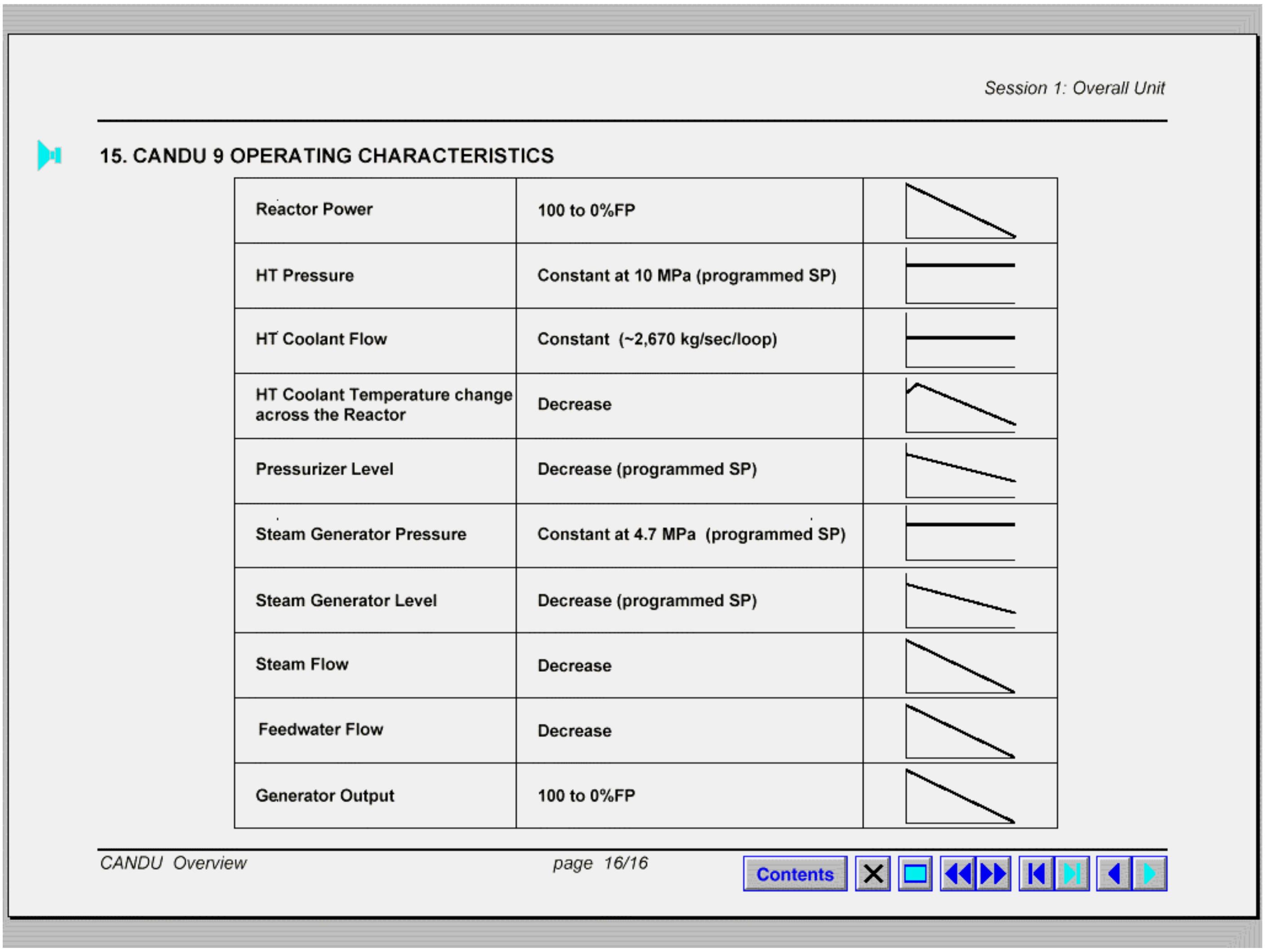
Pressurizer Level decreases in response to the programmed level setpoint decrease of the HT Inventory Control program.

Steam Generator Pressure is kept constant by the Steam Generator Pressure Control program.

Steam Generator Level decreases in response to the programmed level setpoint decrease of the Steam Generator Level Control program.

Steam Flow decreases due to the Governor Valve opening being reduced by the Steam Generator Pressure Control program.

Feedwater flow decreases due to the decrease in Steam Flow.



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15. CANDU 9 OPERATING CHARACTERISTICS

Reactor Power	100 to 0%FP
HT Pressure	Constant at 10 MPa (programmed SP)
HT Coolant Flow	Constant (~2,670 kg/sec/loop)
HT Coolant Temperature change across the Reactor	Decrease
Pressurizer Level	Decrease (programmed SP)
Steam Generator Pressure	Constant at 4.7 MPa (programmed SP)
Steam Generator Level	Decrease (programmed SP)
Steam Flow	Decrease
Feedwater Flow	Decrease
Generator Output	100 to 0%FP

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