## Lesson 10: OVERALL UNIT CONTROL

### Module 1: Boiler Pressure Control

# MODULE 1: BOILER PRESSURE CONTROL (BPC)

## MODULE OBJECTIVES:

**At the end of this module, you will be able to:**

1. **Briefly explain, in writing, the role of BPC during:**
   a) **Warmup;**
   b) **Cooldown.**
2. **Briefly explain, in writing and with a sketch, how BPC maintains the turbine at its operating setpoint.**
3. **Briefly explain, as a sequence of control events, how Boiler Pressure Control responds to:**
   a) **Reactor Trip;**
   b) **Load Rejection.**
4. **Briefly describe, in a few lines, how BPC functions during an increase in unit power output.**

## Introduction

- **The Boiler Pressure Control (BPC) in a typical CANDU generating station will perform the following functions:**

  **(1) . To control boiler pressure under normal operating conditions to a specified setpoint.**

  **(2). To allow warm-up or cool-down of the heat transport system at a controlled rate.**

- **Since, under saturated conditions, steam pressure and temperature are uniquely related, boiler pressure is used to indicate the balance between reactor heat output and steam loading conditions.**

- **Steam pressure measurement is used since it provides a faster response than a temperature measurement.**

- **The Boiler Pressure Control is a digital control loop application with a sampling period every 2 seconds.**

## Basic Principles

- **A steam generator (boiler) is simply a heat exchanger and as such it obeys the standard heat transfer relationship from one side of the boiler (tubes side) to the other (shell-side).**

## Basic Principles

- **Standard Heat transfer relationship can be described as:**

$$\dot{Q} = U.\ A.\ \Delta T$$

**where:**

$\dot{Q}$ = **the rate of heat exchange from the HTS to the boiler water (kJ/s).**
**U = heat transfer coefficient of the tubes (kJ/s/m$^2$)**
**A = tube area (m$^2$)**
**$\Delta T$ = temperature difference between HTS and steam generator inventory.**

- **A and U are a function of boiler design and therefore $\dot{Q}$ is proportional to $\Delta T$.**
- **If reactor power output increases, then more heat must be transferred to the boiler water. $\dot{Q}$ has to rise, therefore $\Delta T$ must also increase.**

- **This increase in $\Delta T$ can be achieved by either allowing the average HTS temperature to increase as reactor power increases (as is the case for a pressurizer installation) or by arranging that the boiler pressure falls, and therefore boiler temperature falls, as reactor power increases (as is the case for a solid HTS design with no pressurizer).**

- **For all units designed with a pressurizer, the first method is employed. Whereas for units without pressurizer, the second method is used.**

## BPC Operation for Units having a Pressurizer

- **Under normal operating conditions, BPC manipulates the** reactor power **output in order to control boiler pressure to the setpoint. The turbine/generator, which is the heat sink for the boilers, is controlled to an operator specified setpoint.**

### "Alternate" or "Reactor Leading" Operation

- **If the unit is operating in the** reactor leading **mode - at low power conditions - the reactor power setpoint is specified by the operator.**
- **Boiler pressure is then controlled to its setpoint by manipulation of the steam loads, i.e., turbine and steam discharge valves.**

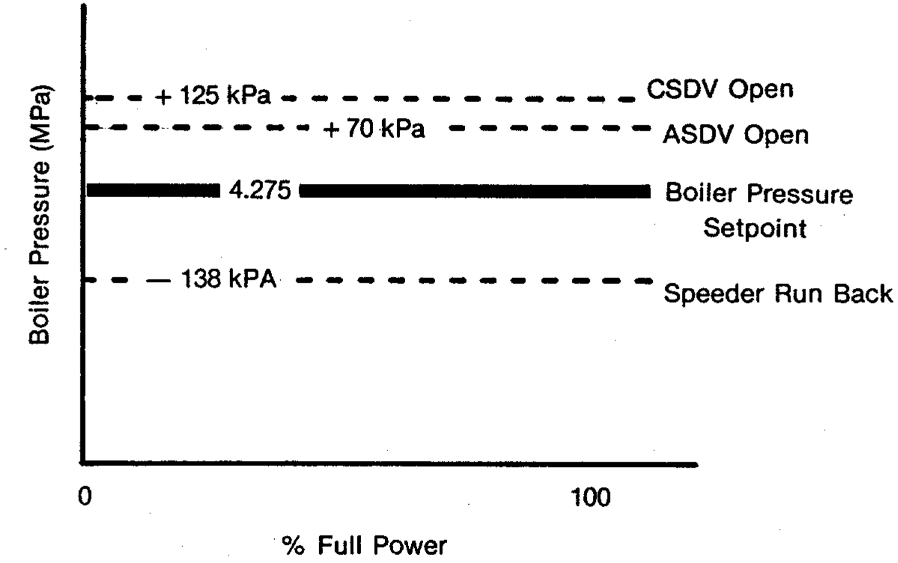

Figure 1: Boiler Pressure and Reject Valve Setpoints.

### Steam Discharge Valve Control

- **The Atmospheric Steam Discharge Valves (ASDV) and Condenser Steam Discharge Valves (CSDV) are, under normal operating conditions, closed due to the introduction of a bias signal.**
- **If, for any reason, the boiler pressure rises above its setpoint by 70 kPa the ASDVs will open.**
- **If the rise in boiler pressure is greater than 125 kPa above setpoint the CSDVs will start to open.**
- **If the positive boiler pressure error is not corrected by the ASDVs and CSDVs a reactor setback will be initiated to correct the thermal mismatch (i.e. correct both the demand and the supply).**

## Response to Reactor Trip

- **Under these conditions heat input to the boilers has been reduced rapidly towards zero.**
- **The turbine output must also be quickly reduced to avoid a gross energy mismatch which could drastically reduce the pressure and temperature of the HTS.**
- **The reduction in heat input will cause a drop in boiler pressure below the setpoint.**
- **The speeder gear will run back to ensure the heat balance between reactor and unit output is re-established at the decay heat level (i.e. take less steam from the boilers).**
- **Any shrinkage in the HTS inventory will be made good by transfer of $D_2O$ from the pressurizer to the HTS or by additional feed from the pressurizing pumps.**

## Load Rejection

- **Firstly the potential turbine overspeed must be prevented. (Turbine design specific information)**
- **The governor/speeder gear will limit turbine speed and prevent an overspeed trip.**
- **In addition the Intercept Valves (IV) will close to prevent steam being fed to the low pressure turbine and the Release Valves (RV) must be opened to dump steam to prevent reheater over pressurization.**
- **When the turbine speed has re-stabilized at 1800 rpm the IV's will re-open and the RV's will close.**
- **Secondly, we must reduce the reactor output by the initiation of a reactor stepback to 2% FP at the instant of load rejection.**
- **Note that poison prevent operation may be necessary to prevent a poison outage, i.e., the unit will be run at 60-70% using its alternative heat sinks - the CSDVs.**

## BPC Operation for Units without a Pressurizer

- **Units with only feed and bleed systems for Heat Transport pressure control are normally run as base load, reactor leading, stations.**
- **The response of the Heat Transport System to transients caused by power maneuvering is very limited.**
- **The Boiler Pressure Control System has a role in limiting the potential swell and shrink of the HTS inventory by maintaining the HTS average temperature essentially constant over the full operating range.**
- **To control the boiler pressure, (the controlled variable) following manipulated variables are used:**
  - **(a)** *Reactor Power*
  - **(b)** *Turbine Steam Flow*
  - **(c)** *Steam Reject Valve (SRV) Steam Flow*
- **The boiler pressure will be decreased from 5 MPa to 4 MPa as unit power is raised from 0 to 100% full power (this is to minimize HTS temperature changes).**
- **This is also the turbine operating ramp. The SRV setpoint is a parallel ramp set 100 kPa higher than the turbine ramp.**
- **Should the boiler pressure rise by more than 100 kPa excess pressure will be released by the small SRVs.**
- **If the positive pressure transient is not corrected by the small SRVs the large SRVs will start to open. Opening of the large SRVs will initiate a reactor setback.**
- **If the boiler pressure falls below the turbine setpoint the speeder gear will run back to a point where the decreased turbine power will be matched**

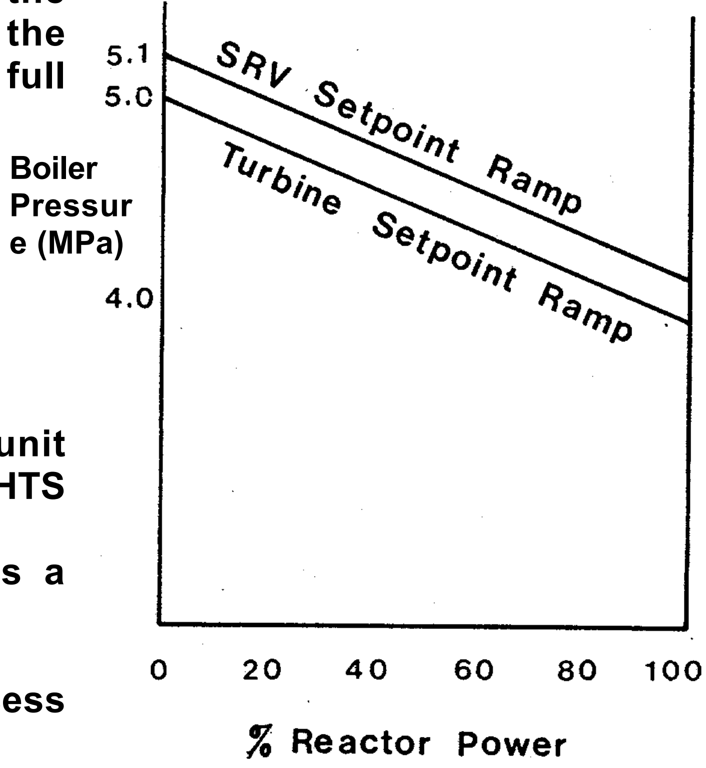

Figure 2: Turbine and SRV Setpoint-Ramps.

## Response to Reactor Trip or Setback

- **The limited response of a feed and bleed HTS to large transients has already been mentioned. It is necessary therefore that, for the transient produced by a reactor trip, control should be as immediate as is possible.**
- **The speed of response is enhanced by using a feedforward signal which will respond to the disturbance which in-turn will eventually cause the control error to appear (the problem is low HTS pressure).**

- **The BPC is a digitally controlled system executing every two seconds. If the present reading of reactor power is less than it was two seconds previously, the control system will decide that the reactor has been tripped or setback. A fast speeder gear runback will be initiated thus anticipating the error and stabilizing the energy balance at a lower level.**

## Load Rejection

- **The problem is again a gross energy mismatch, with maximum input (reactor) and minimum output (electrical power) – the problem is high HTS pressure. The solution is to find an alternate heat sink as soon as possible. This heat sink will be the SRVs.**

- **Again use is made of a feed forward signal, in this case the pressure differential existing across the ESV, GSV combination.**
- **Under normal conditions, with both valves fully open, this pressure difference will be minimal and relatively constant. The load rejection will cause the ESV to close with a resulting rapid increase in the differential pressure (boiler side increases, turbine side decreases).**
- **This increase in $\Delta$P is used as a feed forward signal which triggers the Fast Boiler Pressure Control (FBPC) program. This program executes every 0.5 seconds instead of the normal 2 seconds.**
- **The FBPC program opens the large SRVs fully thus providing an effective heat sink in a much shorter time. In addition, the opening of the SRVs will trigger a reactor setback.**

## Load Rejection…continued

- **Again this accelerated control action should limit the magnitude of the HTS pressure transient and prevent a reactor trip.**
- **The potential turbine overspeeding must be controlled by the governor/speeder gear.**
- **The Intercept Valves and Release Valves operate to stop steam flow to the LP turbine.**
- **The ESV will reopen approximately five seconds after closing when the governing system should once again be in control.**

## Warmup and Cool Down Operation

### Warmup Mode

- **At some point in the start up procedure for a CANDU unit, the reactor heat sink must be transferred from the** shutdown cooling system **to the normal primary heatsink, i.e.,** the boilers**. This transfer is usually effected at a HTS temperature of approximately 170°C depending upon unit site.**
- **Once the boilers have been established as the primary heatsink the temperature of the HTS can be raised at a pre-determined rate by manipulation of the boiler pressure.**
- **Consider a steady reactor thermal output, say 2% full power. The energy train can be made to balance by discharging steam to atmosphere from the boilers via ASDVs or SRVs, i.e., 2% heat input and 2% output.**
- **If we restrict the steam output from the boilers by closing the reject valves slightly, we now have an energy imbalance at the boiler stage. More heat energy is entering the boilers than is leaving and the boiler pressure and temperature will therefore increase.**

## Warmup Mode……continued

- **Removing less steam from the boilers will increase the boiler pressure resulting in a higher saturation temperature.**
- **The higher boiler temperature will raise the heat sink temperature for the HTS and so the HTS temperature will rise accordingly (note that the HTS temperature is dictated by the boiler temperature).**
- **Recall the equation describing heat transfer between the HTS and the boilers:**

$$\dot{Q} = U.\ A.\ \Delta T$$

- **To maintain the $\Delta T$ constant the HTS temperature will have to increase since $\dot{Q}$, U and A are all constant quantities.**
- **Eventually we will have reached a situation where, for a constant heat input from the reactor, we have raised both boiler and HTS pressures and temperatures.**
- **The warmup process can now be continued by requesting an increase in boiler pressure which will be accomplished by a further closing of the steam discharge valves.**

## Cool-down Mode

- **This mode is used to cool the HTS when bringing the unit down from a full power operating state. Again use is made of either the SRVs or the ASDVs to control boiler pressure.**
- **In this instance the process is initiated by an opening of the steam discharge valves.**
- **Again, for a steady reactor thermal output, the change in boiler pressure, and therefore temperature, must cause a change in HTS temperature in order to maintain a constant ∆T between HTS and Boilers.**
- **In theory this progressive opening of the discharge valves should reduce boiler pressure to atmospheric but in practice, as boiler pressure falls, the discharge steam flow rate of the valves is insufficient to drop the boiler pressure further.**
- **When the valves are fully open BPC has lost control of the cooldown – this usually happens at about 140 C temperarture.**
- **Thus, before the steam discharge valves reach their fully open state, the heat sink for the system is transferred to the shutdown coolers.**
- **Again, according to station design, this transfer will take place at approximately 170°C to ensure a controllable configuration.**

## Boiler Pressure Response to A Requested Increase in Electrical Output

- **A request for** increased electrical output **will create an error signal between the existing output and the new setpoint.**
- **This error signal will cause the speeder gear to run up and thus increase the steam flow to the turbine.**
- **This increased steam flow will result in an increased electrical output and eliminate the electrical error which had been created.**
- **However, the increased steam flow will inevitably cause boiler pressure to fall.**
- **The increased governor valve opening results in an increased steam pressure on the turbine side of the governor valve.**
- **This pressure increase is used as a feedforward signal which can be used to modify the reactor power setpoint in advance of the negative boiler pressure error developing.**
- **In practice the feedforward signal will limit the size of the negative boiler pressure transient but is unable to eliminate it completely.**
- **The resulting drop in boiler pressure is used as a feedback signal to the boiler pressure control program. This will cause a further adjustment to be made to reactor power output and thus return the boiler pressure to its setpoint.**

## BPC Assignment

**1. Briefly state the two main functions of the Boiler Pressure Control System.**

**2 . Briefly explain how the Boiler Pressure is manipulated to achieve a controlled warm-up mode.**

**3 . Briefly explain the method of cooling the HTS by means of Boiler Pressure control.**

**4. Briefly explain in writing, and with a sketch, how the turbine is kept at it's operating setpoint by the BPC.**

**5. For a Pressurizer controlled HTS, list a suggested sequence of control reactions in the event of:**

**(a) Load Rejection**

**(b) Reactor Trip.**

**6. Describe briefly the BPC's role in a demanded increase of unit power output when in Reactor Leading Mode.**

# Lesson 10: OVERALL UNIT CONTROL

# MODULE 2: UNIT CONTROL CONCEPTS

## MODULE OBJECTIVES:

**At the end of this module, you will be able to:**

1. **Sketch and label a block diagram which illustrates the gross energy balance of a typical CANDU generating station.**

2. **State the five major control systems necessary for maintaining the overall energy balance while maintaining stable plant control.**

3. **Briefly, explain in writing, the major differences between Reactor Leading and Reactor Lagging modes of control in response to a change in unit power output.**

## Energy Balance

**A typical generating station can be considered as a series of energy sources and sinks which together provide an overall energy balance.**

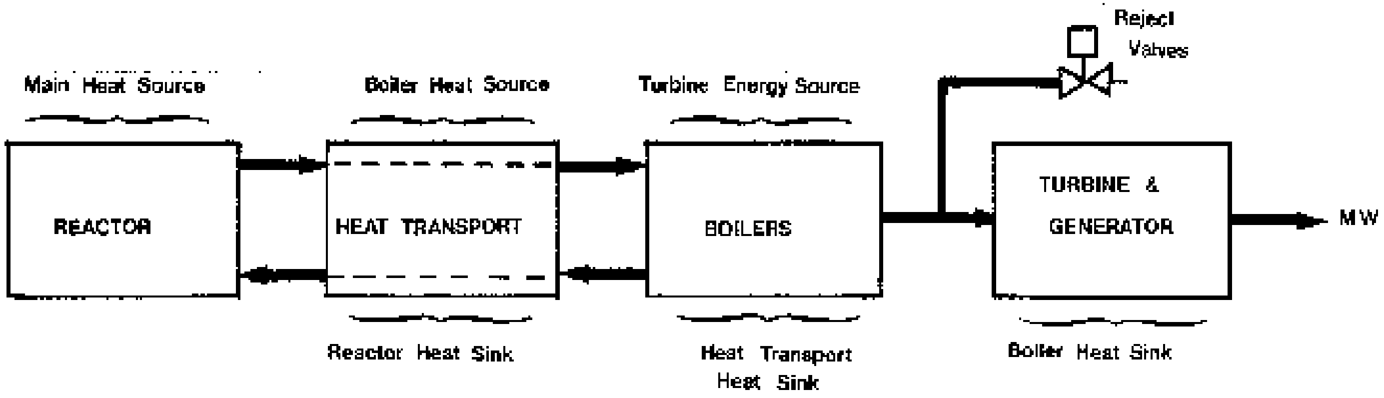

Figure 1: Gross Energy Balance of a Generating Station.

- **The reactor provides he heat energy input for the system.**
- **The heat generated, by the fission process, is carried to the boilers by the heat transport system.**
- **The boilers convert this transported heat to a source of steam which is used to drive the turbines.**
- **The turbine drives the generator to provide electrical power to the grid system.**
- **An alternative final heat sink, in the form of reject valves, is provided in the event that the turbine is not available.**

## Maintaining the Energy balance

- **This integrated plant operation is stable as long as no part of the energy chain is mismatched or broken.**

- **If one portion of the chain is disturbed the system interactions will likely cause control corrections to be necessary in other areas. For example consider an unexpected decrease in boiler feed water supply.**

- **The boilers now appear as a smaller heat sink for the HTS and so less heat will be extracted from the HTS inventory.**

- **The temperature and therefore pressure of the heat transport system will increase and action must be taken to relieve pressure in the heat transport system possibly by decreasing or removing the heat source, i.e., reactor.**

- **In all of the control situations to be discussed, an upset condition will be controlled by:**
  1) **re-establishing stable control at the present power level.**
  2) **re-establishing stable control at a lower power level.**

## Overall Unit Control Concepts

**There are two methods of overall unit control used in nuclear generating stations. The choice is dictated by the station design and its *intended mode of operation*. These control modes are usually referred to as:**

- **reactor leading (…or turbine following)**
- **reactor following *(…or t*urbine leading)**

## Reactor Leading (Turbine Following)

- **This is the mode used for most base-load stations.**
- **Essentially the station turbine load and hence the electrical output is determined by the reactor power set-point.**
- **Any changes in electrical output will first require a change in reactor output.**
- **The electrical output change will follow the change in reactor power once the reactor thermal power change has been transferred to the heat transport system and then to the boilers to create more steam for the turbine.**
- **In summary then, a reactor leading design requires that the desired increase in power be requested as an increase in the reactor power setpoint.**
- **The increased reactor power now transfers more energy to the heat transport system which in-turn provides more energy to the boilers to begin to raise the boiler pressure at the present steam flow demand.**
- **As the boiler pressure is increased, the speeder gear can be run up to admit more steam to the turbine and thus raise the electrical output from the turbine/generator set.**

## Reactor Following (Turbine Leading)

- **This is the preferred mode of operation from the point of view of the bulk electric power system operator.**

- **The generating unit will respond immediately to requested changes in electrical power production and will provide this output from the energy that already exists in the boilers.**

- **The additional energy taken from the boilers will cause the boiler pressure to drop creating a boiler pressure control error which in-turn will request a higher reactor power setpoint**

- **The change in reactor power is managed by the overall unit control system in the form of a requested reactor power change to restore the boiler pressure.**

- **In many cases it is not desirable to have frequent changes in reactor power output, this situation can be avoided by having other (non-nuclear) units on the bulk electric system that respond more quickly to changes in demand.**

- **In summary then, a reactor following design allows an immediate electrical power change response to be made which would cause, for example, a decrease in boiler pressure.**

- **This decrease in boiler pressure initiates a reactor power increase request which raises the reactor power level.**

- **The increased reactor power transfers more energy to the heat transport system which in-turn provides more energy to the boilers to recover the boiler pressure at the increased steam flow demand.**

## Operation of Reactor Leading Mode

- **Consider the requirement for an increase in unit power output.**
- **The operator will increase the setpoint of the Unit Power Regulator (UPR).**
- **A control error will be created between the existing unit electrical output and the new requested unit Power setpoint.**
- **This error signal develops the new setpoint for the Reactor Regulating System (RRS), changing the reactor power.**

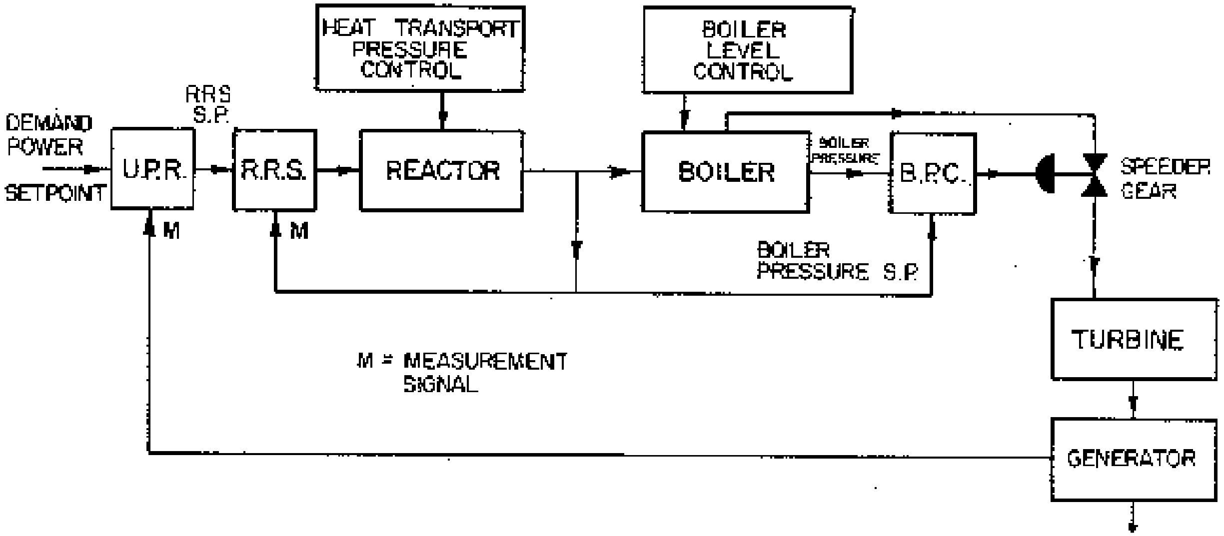

Figure 2: Simplified Reactor

- **This new RRS setpoint will cause an increase in the reactor power.**
- **This additional heat energy output will attempt to increase the temperature of the Heat Transport System which in turn elicits a response from the Heat Transport System Pressure Control to maintain the pressure at the fixed setpoint.**
- **The increased heat energy is supplied to the Boilers where a control response from the Boiler Level Control and the Boiler Pressure Control may be necessary to maintain the correct boiler level and pressure conditions.**

## Operation of Reactor Leading Mode…continued

- **Any boiler pressure deviation from the pressure setpoint will cause the speeder gear (and hence the turbine governor valves) to be adjusted.**
- **In the case of a power increase to the grid, the steam flow to the turbine will be increased to hold the boiler pressure relatively constant, i.e., boiler pressure is held at the pressure setpoint at the higher reactor power by manipulating steam flow.**
- **The increased turbine/generator power output will result in an increased electrical output.**
- **It can be seen that the overall unit control loop is closed by a feedback path from the generator to the UPR.**
- **Control action will continue, i.e., reactor power increases, until the measured electrical output of the unit is equal to the new UPR setpoint.**

## Operation of Turbine Leading Mode

- **Consider the request to increase unit power output.**
- **The setpoint increase will be input to the** Unit Power Regulator **(UPR).**
- **The resulting control error between the UPR setpoint and the actual electrical power output will cause a direct adjustment of the speeder gear to increase steam flow to the turbine thus increasing the unit's electrical output.**
- **Once the actual electrical power output meets the new demanded UPR setpoint, speeder gear position will be held steady.**

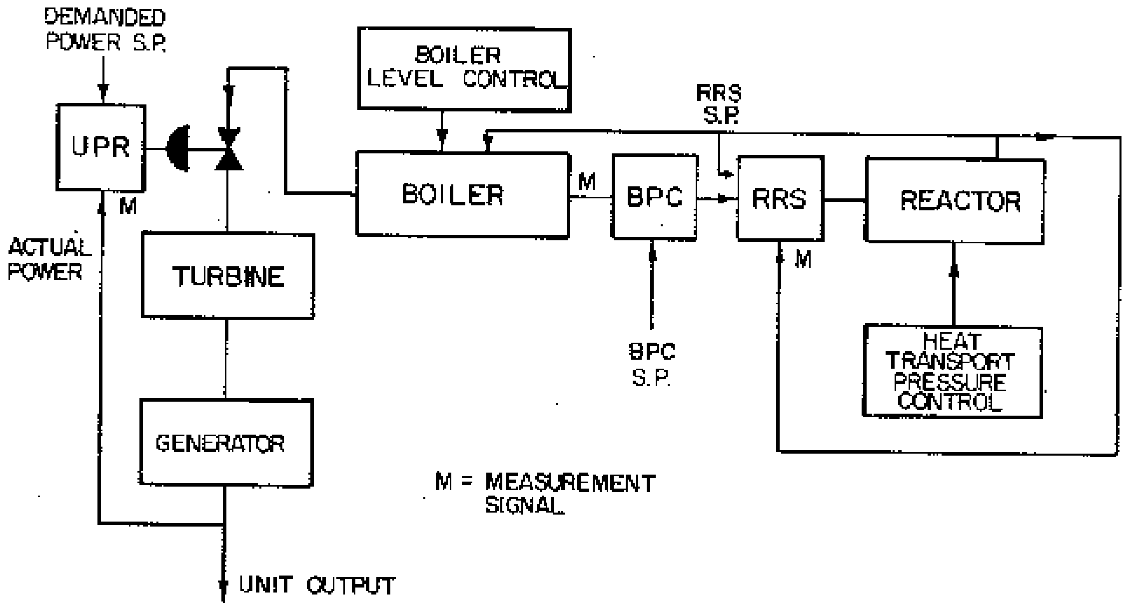

Figure 3: Simplified Reactor Following Control

- **The increased steam demand to the turbine will cause a** decrease in boiler pressure**.**
- **The resulting pressure error signal from the BPC develops the new** setpoint signal **for the Reactor Regulating System.**
- **The RRS will now increase reactor power until boiler pressure is restored with the higher steam flow rate.**
- **The unit is once again in a** stable condition**, supplying the higher electrical output while maintaining the boiler pressure with the higher reactor power.**

## Overall Unit Control Summary

- **Two general points should be remembered about overall unit control.**

**(1) The basic unit control functions are performed by five major control loops. These are:**

- **(a) Unit Power Regulator (UPR) controls the overall unit power output. It is a primary interface between the operator and the control system.**
- **(b) Reactor Regulating System (RRS) controls the power and rate of change of power of the reactor.**
- **(c) Boiler Pressure Control (BPC) controls the boiler pressure via the speeder gear (and hence turbine governor valves) or via the steam reject valves. Note that in the Reactor Leading mode the Boiler Pressure Setpoint is a function of Reactor Power, i.e., a variable setpoint.**
- **(d) Boiler Level Control (BLC) controls the boiler level as a function of unit output power.**
- **(e) Heat Transport System Pressure & Inventory Control (P&IC) regulates heat transport system pressure. Pressurizer heaters and steam bleed valves and/or feed and bleed valves are the methods for pressure regulation.**

**(2) All CANDU generating stations are designed to be operated under automatic control. The operator's normal function is to initiate any change of operating conditions or to intercede as needed if automatic control action is impaired for any reason, e.g., equipment failure or during run up and run down operations.**

## Assignment

**1 . Sketch and label a simple block diagram which illustrates the energy transfer in a typical CANDU generating station.**

**2. Overall plant control is maintained by five major control loops. List the loops and state their principle function.**

**3. Sketch the control block diagram for a reactor leading and for a reactor following control configuration.**

**4 . Briefly explain the control responses to a request for an increase in station power output for:**

**(a) A Reactor Leading Unit**
**(b) A Reactor Following Unit**

# Lesson 10: Module 3: OVERALL UNIT START-UP

# MODULE 3: UNIT STARTUP

## MODULE OBJECTIVES:

**At the end of this module, you will be able to:**

1. **State the reactor conditions, with regard to poison addition, control and safety systems availability, moderator level, which must exist prior to a start up being commenced.**

2. **List the requirements, with regard to deaerator levels and heaters, pump availability, and condensate hot well level, which must be satisfied to establish the feed water path from condenser to boilers.**

3. **Sketch a simple graph illustrating a method of raising HTS pressure and temperature between shutdown and operating state.**

4. **Briefly explain why the shutdown cooling HX's are isolated before the main HTS circulating pumps are put into service.**

5. **Briefly describe a method to bring the reactor to criticality using poison extraction and liquid zone control.**

6. **List the checks that should be made before, and during, turbine run up particularly before passing through the critical speed range.**

## Introduction

- **This module outlines the major activities that must be performed to restart a unit after a prolonged outage, e.g., a maintenance shutdown.**

- **An actual start-up procedure is specific to a particular station location and is too long and detailed to be described in a course of this type but the full procedures can be found in the station operating manuals.**

## Reactor & Shutdown Systems

- **Recall from the lessons on the Reactor Regulating System (RRS) and Shutdown Systems (SDS) that these systems must be operative before reactor criticality can be considered.**

- **The RRS is designed to control the reactor with a normal Xenon load of approximately -28 mk.**

- **At the end of a maintenance outage exceeding a few days the reactor will be devoid of all Xe-135.**

- **To provide the necessary negative reactivity worth for the RRS to function correctly, it will be necessary to provide an "equivalent Xenon load" of approximately -28 mk by moderator poison addition.**

- **In addition a guaranteed shutdown state (GSS) will have been provided for the reactor shutdown maintenance work conditions. GSS is an administrative set of controls to ensure that positive reactivity can not be added to the core.**

## Reactor & Shutdown Systems….continued

- **Both these requirements can be met by poisoning (i.e. neutron absorbing) the moderator over and above the steady state Xenon load requirement. This poisoning is achieved by the use of either Boron or Gadolinium – both strong neutron absorbers.**

- **It is also important that the moderator level is at the correct depth before criticality is achieved.**

- **Failure to provide this correct level would mean that the total reactor power output would not be shared more or less equally by all of the available fuel bundles.**

- **Too low a moderator level provides the risk, particularly as reactor power levels are increased after criticality has been achieved, that some fuel bundles and fuel channels could be overrated.**

## Criticality

- **The reactor will be taken to criticality by poison removal.**
- **As the over poisoned moderator will shield the Shutdown System ion chambers, the rate log trip. will be lowered, typically to 4% power/second.**
- **The high power trip will be also set lower, typically at 10% full power.**
- **Sufficient ion exchange (IX) capacity must also be made available. If Boron is being used to poison the moderator, at least two fresh IX columns and one other with removal capacity will be necessary.**
- **The moderator poison level (ppm) can gradually be reduced as the poison is extracted, allowing the neutron population to slowly increase.**

## Condensate/Feedwater System

- **During extended shutdowns, decay heat from the reactor is being removed by the shutdown cooling system.**

- **In preparation for power operation, and before criticality is achieved, and significant neutron power becomes available, the boilers must be established as the principle heat sink for the system.**

- **The main heat transport system must be placed in service in order to carry the fission heat and decay heat from the reactor to the boilers**

- **So then, it is necessary therefore, to ensure that the condensate, feedwater, boiler and primary heat transport systems are available in a fully operational condition.**

**To make the Condensate *and* Feedwater systems available it is necessary to:**

- **first ensure that there is a sufficient level of feedwater condensate inventory in the condenser hotwell and that the low pressure feed heat exchangers (flowpath) are available for use.**

- **It will also be necessary to establish the condensate/feed flowpaths, by operating the appropriate valves, from the condenser hotwell to the deaerator and from the deaerator to the boiler.**

## Condensate/Feedwater System…continued

- **To prevent thermal shock and stress conditions, the differential temperature between the HTS Inventory and the Feedwater temperature should be restricted to less than 150 C difference.**

- **To assist with this, a minimum temperature must be established in the deaerator storage tank by switching on the D/A storage tank electric immersion heaters ( and the minimum D/A storage tank level must be established to allow immersion heater operation) or by admitting start-up warning steam (if available).**

- **The capacity of these heaters is such that the heating up process will take about thirty-six hours. This time can be reduced by using the main boiler feedpumps in a recirculation mode to provide some additional pump heat.**

- **The condensate extraction pumps (CEP) should be tested and the appropriate number, typically one at this stage, selected "ON" with the remainder in "AUTO" or "STANDBY". If no deaerator makeup is necessary the CEP will recirculate flow to the condenser hot well.**

- **There must also be a sufficient level of water (i.e. inventory) in the boilers and boiler feed is, at this stage, being controlled by the small feed valve.**

- **Note that as the steam and feed flows are effectively zero, boiler level control will be by either single element or manual control.**

## Condensate/Feedwater System…continued

- **There is now a supply of cooling feed from the condenser hotwell to the boilers and the boilers are now available to become the heatsink for the reactor.**

- **The boilers must now be put into the hot shutdown state (typically 4.9 MPa and 265 C) using the Boiler Pressure Control System (BPC) (in warm-up mode) by raising boiler temperature using heat energy from the deaerator storage tank and the Boiler Feed Pumps.**

- **If the Heat Transport System is available, the heatsink can be transferred from the shutdown coolers to the boilers.**

## HTS Cold and Depressurized to Hot and Pressurized

- **With the HTS in the cold and depressurized state and the shutdown cooling system operative, the HTS temperature will be typically 40∞C or less.**
- **The HTS Pressurizer must be isolated from the main circuit**
- **Saturation conditions will be established in the pressurizer by means of electric heaters.**
- **Before proceeding, it is important to check the level of the $D_2O$ storage tank to ensure a known starting condition inventory.**
- **Remember there must be sufficient capacity available to accommodate the large inventory swell as the system is taken to its operating state.**
- **The bleed condenser is not required until HTS pressure exceeds approximately 2 MPa – up to this pressure the bleed condenser can be bypassed to admit the bleed flow to the purification circuit.**
- **A sufficient quantity of $D_2O$ must be present in the Bleed Condenser to enable saturation conditions to gradually be established as the bleed temperature rises.**

## HTS Cold and Depressurized to Hot and Pressurized….continued

- **The pressure control system for the bleed condenser, both reflux and spray control, will not be needed at this time and can therefore, be placed in "manual," with both valves closed.**

- **The bleed cooler is, however, still required as the inventory swell to the $D_2O$ storage tank must be routed via the ion exchange columns and the limiting temperature of less than 65∞C (to prevent resin breakdown) will still apply.**

- **The temperature controllers should be placed in "Automatic" with the setpoints at the correct settings.**

- **Also, at this stage, ensure that the gland supply to the heat transport pumps is available and that the gland filters are in service.**

- **Heat Transport pressure control will be in Wide Range (Solid Mode) and if the station has two HTS loops, they will normally be isolated from one another at this stage.**

## Initial HTS Pressurizing

- **Before pressurizing the HTS, it should be remembered that the heat transport system has** metallurgical **constraints applied to it and that pressure and temperature must be adjusted according to the method outlined in the operating manual.**

  - **Briefly this involves raising pressure, at a** constant temperature **(less than 40∞C) to 2.7 MPa(g) and then raising temperature at** constant pressure **to approximately 175∞C.**

  - **Pressure is then raised at this intermediate temperature until the working pressure of 8.6 MPa(g) is reached. Temperature could then be increased to the normal "hot" temperature of 265 C.**

- **At this time reactor criticality has not been achieved but the boiler and feed water system is in the zero power hot state.**

- **The transfer of the heat sink from the shutdown cooler HXs to the boilers can now take place.**

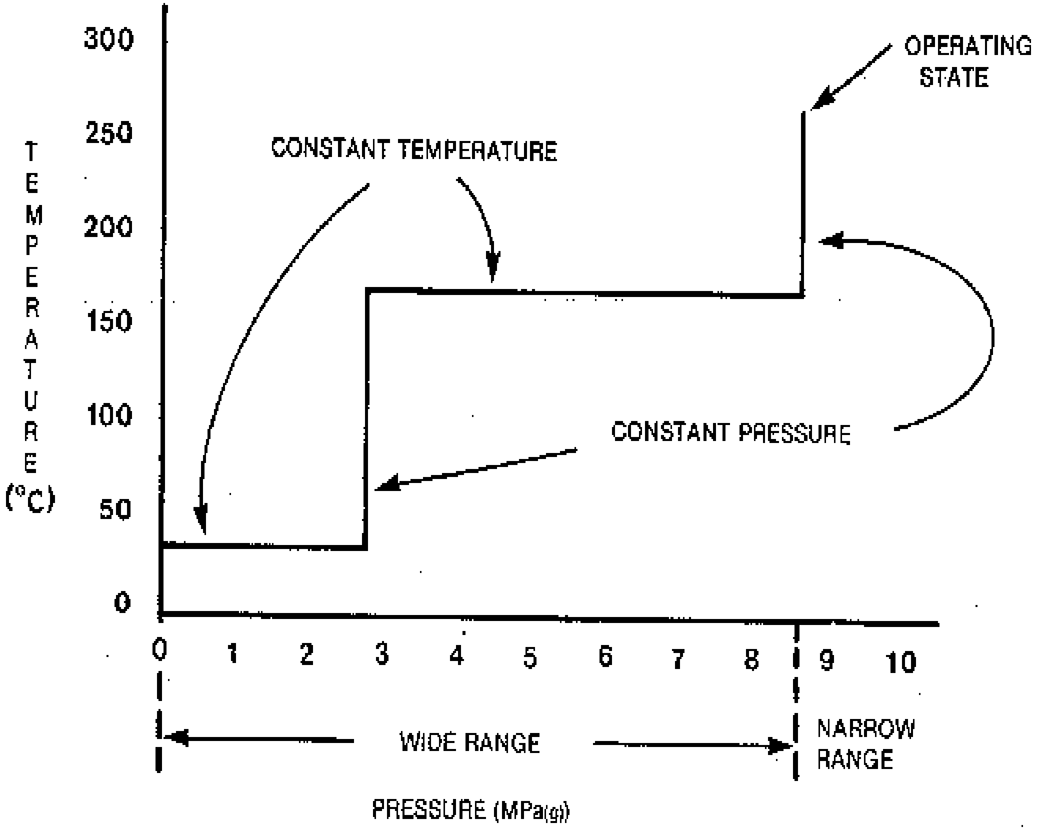

**Figure 1: Typical HTS Run-Up Pressure/Temperature Prof**

## Heat Sink Transfer to the Boilers

- **The HTS temperature can now be increased by raising the setpoint of the shutdown cooling HX's to just below 100∞C.**

- **Before the whole of the heat transport system can be circulated, in order to use the boilers effectively as a heatsink (non-thermosyphoning), the main HTS circulating pumps must be started.**

- **Before each Main HTS pump is started the associated shutdown cooling pump in that loop must be shut down and the HX's isolated.**

- **If this was not done the large main HTS pumps would cause reverse flow through the shutdown coolers and possibly burn out the shutdown cooling pump motors due to the increased loading.**

- **Note that for good practice, the pressurizer should be connected to the main circuit before the main HTS pumps are started to help prevent any pressure wave or disturbance from stressing the main circuit (or perhaps causing an inadvertent trip on high pressure.**

## HTS Warm-up

- **The HTS inventory is now circulating and temperature will increase somewhat due to pump and subcritical reactor heat.**
- **HTS temperature will now be approximately 100∞C at a pressure of 2.7 MPa(g).**
- **The programmed run-up of temperature is continued to 175∞C before the pressure is increased and then the reactor must be made critical.**

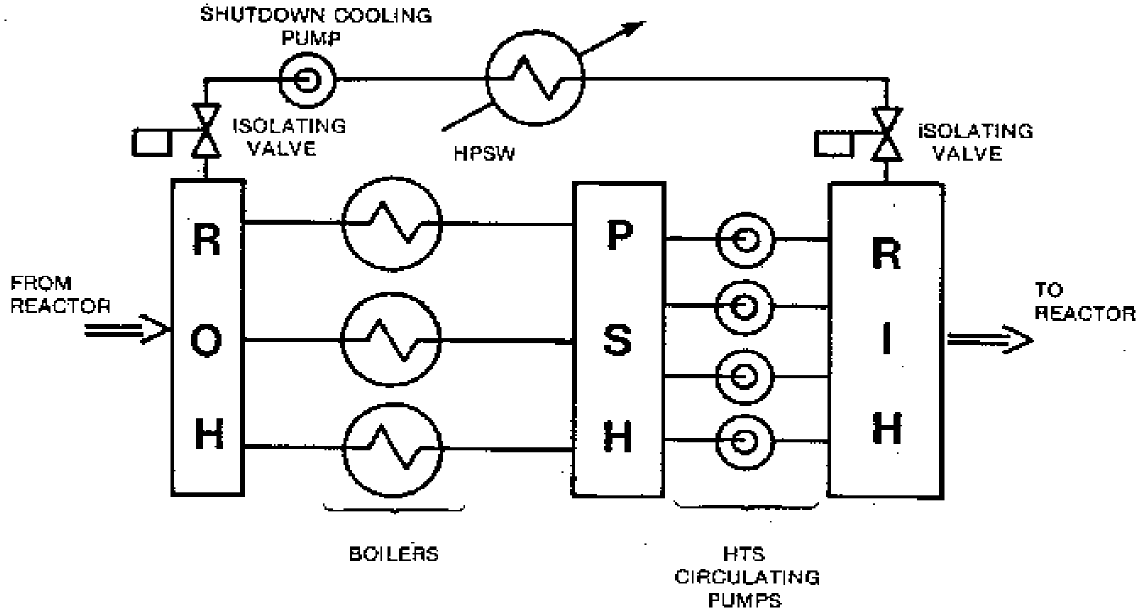

Figure 2: Typical Shutdown Cooling System Circuit.

## Approach to Criticality

- **If all reactor parameters and control systems are correct the approach to criticality can continue.**

- **In general the method is to apply a "Hold Power" command to the reactor control system while removing moderator poison via the IX columns.**

- **As poison is removed reactor power will begin to increase due to the increase in neutron population.**

- **This power increase will be countered by an increase in zone level to keep a steady power level.**

- **When the zone level reaches some predetermined magnitude, typically 60%, in the continued attempt to hold the power level constamt as before, an increase in power will be demanded by the operator.**

- **This will cause a lowering of zone level. When zone level reaches, about 25% a "Hold Power" command will again be input to the RRS.**

- **Poison removal continues and the foregoing procedure is repeated. Recall that if power doubles for a known increase in reactivity (change in zone level) a further, equal, increase will cause the reactor to go critical (Power Doubling Rule).**

- **Thus the approach to criticality can be carefully defined and controlled.**

## Approach to Criticality…continued

- Post Criticality checks **would be performed to see that the liquid zones recover to the exact starting level following a small power increase and decrease sequence (as opposed to a discrete change in level to cause an associated change in reactor power)**

- **Once the reactor is confirmed critical, power can be raised to the range of $10^{-4}$ FP with zone levels typically at 35-40%.**

- **Before power is raised further, various checks will be completed to ensure that all related RRS systems and functions are performing correctly.**

- **Power control is in logarithmic mode (**log range ion chamber monitoring**) and when power approaches 5% FP, Rate Log Trip settings can be set to normal operating limits of 10% power/per second, and the High Power Trip point will also be increased (typically to 45% FP).**

- Pre-linear range checks **could now be completed to be sure that the linear range in-core flux detector signals are valid and that the channel outlet temperatures for each channel is as expected (no flow blockages)**

## Transfer to Narrow Range Pressure Control

- **The wide range HTS pressure controller set points will now be steadily increased to approximately 8.5 MPa(g).**

- **When the pressure indicated on the two wide range pressure controllers has stabilized, one of the loop interconnecting valves can be opened.**

- **Using the narrow range controller which takes its measurement signal from both HTS loops - reject the other two controller signals by setting one setpoint high and one low. Adjust the setpoint of the selected, median Narrow Range Controller such that it just matches the operating wide range balanced signals.**

- **HTS Control can now be switched to Narrow Range (Normal mode). The three pressure controller set points are staggered with the controller which looks at both loops set at the operating setpoint and the other controllers set one slightly lower and the other slightly higher than that setpoint.**

- **Before the HTS system is taken to its full operating temperature and pressure the bleed condenser must be placed in service. Saturation conditions should have been established whilst it was isolated and the reflux and spray controllers should be set to their normal operating setpoints and placed on automatic.**

- **The "through condenser" mode can now be established by routing the bleed flow into the condenser. Checks must be made as the bleed condenser begins to function to ensure that bleed condenser level is being correctly controlled to the setpoint of 0.9 meters and that the bleed cooling heat exchanger control is performing as expected.**

- **HTS temperature can now be increased to its operating setpoint and at this stage the unit is functioning with the boilers as final heat sink in conjunction with SRVs or ASDVs.**

## Turbine Run Up

- **During the period of HTS warmup and achieving reactor criticality the turbine must be prepared for service. The turbine would be on turning gear and eccentricity would be carefully monitored to ensure that it is within acceptable limits.**

- **The condenser vacuum must also be established by means of the vacuum (hogging) pumps and the CCW flow must be started.**

- **It is important that all turbovisory parameters are carefully monitored during turbine run-up and that all turbine auxiliary systems are operative.**

- **Steam can now be admitted up to the ESV's and the turbine run-up can now commence. The run-up can either be manually or computer controlled up to 30R/S (1800 RPM) unsynchronized.**

## Manual Turbine Speed Control

- **Providing that all the preliminary turbine system checks are OK (lube oil, seal oil, stator and rotor cooling, etc.), the ESVs can be just opened to roll the turbine off the turning gear up to about 5R/S (300 RPM). The turning gear should have-disengaged at about 4 R/S.**
- **Continue to open the ESV's to raise the turbine speed up to about 10 R/S.**
- **The exhaust steam to the condenser should have lowered condenser pressure to less than 20kPa(a).**
- **Further increase turbine speed to about 15 R/S and once again recheck all turbovisory parameters.**
- **Hold this turbine speed until the condenser pressure falls below 10kPa(a) and lube oil temperature approaches 40∞C (prevents oil whip).**
- **Further open ESVs to raise speed to 20 R/S, again checking all turbovisory parameters.**
- **The condenser vacuum unloading trip should now be armed.**

## Generator Synchronization

- **Electrical control and distribution systems for the generator must now be readied to allow electrical generation.**
- **Usually manual voltage regulation (MVR) is selected.**
- **The switchyard main breaker is confirmed opened.**
- **Rotor (hydrogen) and stator (water) cooling systems must be in service. Rotor current to the main generator can now be applied to bring rotor temperature above 30∞C.**
- **The turbine and generator set must be taken through the critical speed range. The critical speed range for the turbine is 20.5 - 23 R/S, while that of the generator is 26 - 27 R/S.**
- **As a result, the ESVs must be opened steadily and without pause as speed is increased from 20 to 28 R/S. If the turbovisory parameters do not stay within limits (vibration > .15 mm is acceptable in critical speed range), speed must be brought back down to 20 R/S and the equipment must be inspected.**
- **The ESVs should now be fully open and the governor system should have taken over turbine speed control (it is at its lower limit). The turbine can now be taken up to synchronous speed (30 R/S, 1800 RPM) by the speeder gear under manual control. If computer control had been selected the computer run-up would stop at this point.**

## Generator Synchronization…continued

- **Generator excitation is now adjusted via the MVR until the generator terminal voltage is at its correct setting (typically 24 kV). Control can now be switched to automatic voltage regulation (AVR) using a bumpless transfer technique.**

- **At this time reactor power would be increased, typically to about 10% FP. Any extra steam over the rotational requirements for the turbine would be discharged via the ASDV's.**

- **Synchronization of the generator to the grid can now take place.**

- **Generator voltage and frequency are matched to grid voltage and frequency by adjusting the AVR setpoint (voltage) and speeder gear setting (frequency).**

- **When the frequency, phase and voltages of the running and incoming busses are equal, the main generator breaker can be closed connecting the generator to the grid.**

## Raise Power to Operating Limit

- **The unit is now supplying power to the grid. The speeder gear can now be transferred to automatic control. Reactor power and therefore unit output power can now be progressively increased.**

- **Reactor control will transfer to linear mode (from log mode) at about 15% FP with an adequate deadband to prevent transfer cycles.**

- **As power is increased the high power trip setpoint will be progressively increased. HP feedheaters usually start to come into operation at about 25% FP.**

- **As reactor power increases the Xenon load will also increase.**

- **If boron was used as a moderator poison the rate of boron extraction via the IX columns must be regulated to match the rate of increase in Xenon-135.**

- **If gadolinium is used the burnout rate of gadolinium closely matches the growth rate of the Xenon so less IX column flow control is required.**

- **Remember that the procedure described above is only very general and addresses only some of the major considerations in a unit re-start. Any restart will be unit specific and fully detailed in the appropriate operating manuals.**

## Assignments

1. **State the, major reactor conditions which must exist prior to a start up being commenced.**

2. **List the requirements which must be satisfied in order to establish the feedwater path from condenser to boilers.**

3 . **At what level, and why, should the $D_2O$ storage tank be prior to HTS warm up.**

4. **State the control methods applied to the bleed condenser and bleed cooler during HTS warmup.**

5. **Sketch a simple graph illustrating a method of raising HTS temperature and pressure between shutdown and operating state.**

6. **What could be the possible consequence, and why, of not isolating the shutdown cooler before the main HTS pumps are started.**

7 . **List a sequence of control operations that could be used to achieve reactor criticality by poison removal.**

8. **List the sequence of checks made during the run-up of the turbine. Detail more fully those made before, during and after passing through the critical speed range.**