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HEAT & THERMODYNAMICS

MODULE B.2

STEAM GENERATOR

Heat & Thermodynamics

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STEAM GENERATOR

Course Objectives

1. You will be able to explain how the temperature difference between the steam generator and the PHT system changes during a "crash-cool" exercise.

2. You will be able to state how the PHT average temperature is affected by increasing the thermal resistance of the steam generator tubes.

3. You will be able to explain why the programmed steam generator level increases with power.

4. You will be able to explain one problem concerning high boiler level and three problems concerning low boiler level. You will be able to state the control action which is designed to overcome these problems.

5. You will be able to state the three elements used for boiler level control and explain why they cannot be used at low loads.

6. You will be able to explain the response of the station control system to a falling boiler pressure when control is in the 'normal' mode and the control of the speeder gear is in 'auto'.

7. You will be able to explain why the BPC program terminates at 170°C when in the 'cooldown' mode.

8. You will be able to explain how raising the pressure of the steam generator improves the efficiency of the steam/water cycle.

9. You will be able to explain the limitation on raising the steam generator pressure in the CANDU system.

We have examined the basic thermodynamic principles and must now apply these principles to the operation of the steam generator and finally the reactor.

The steam generator removes the heat from the reactor under normal conditions. The heat which is removed from the fuel in the reactor channel by the heat transport D_2O is rejected in the steam generator to the lower temperature light water system.

The steam generator heat transfer takes place at the tube bundles through which the primary heat transport fluid, flows and around which the feedwater flows.

By varying the rate of heat removal in the steam generator we can control the rate at which the heat transport temperature changes or we can ensure that it remains constant, depending upon the power manoeuvring at the time.

In addition to acting as the major heat sink for the reactor the steam generator produces high quality working fluid that may be used to produce mechanical power in the steam turbine.

The heat that is transferred from the PHT system to the steam generator depends upon the temperature difference which exists between the D_2O and the lightwater in the steam generator.

As the temperature difference increases, more heat is transferred. In a "crash-cool" exercise, this is exactly what happens. By rejecting steam from the steam generator to lower the pressure, the temperature falls as well and increases the temperature difference between the steam generator and the reactor. As a result, more heat is transferred and the cool-down rate of the reactor is increased.

The heat which is transferred also depends upon the thermal resistance of the tubes in the steam generator. If these tubes become coated with oxide or other material, the thermal resistance will increase which means that a higher temperature will be needed in the PHT system in order to transfer the same quantity of heat.

B.2.1

Explain how the temperature difference between the PHT system and the steam generator changes during a "crash-cool" exercise.

B.2.2

Explain how an increase in thermal resistance, across the steam generator tubes, affects the average PHT temperature.

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Level Control

It is important that the mass of light water in the steam generator remains constant to provide an adequate heat sink capacity for the reactor.

We have already seen that the liquid in the steam generator will expand as the temperature rises. This expansion will cause an increase in the level of liquid in the steam generator.

Do this exercise and compare your answer with the notes at the end of the module.

B.2.3

Feedwater in the steam generator is heated until the temperature rises from 170°C to 250°C. Determine the percentage increase in volume that would occur due to this temperature rise.

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In addition to this increase in level there is another effect which will occur. As boiling takes place steam bubbles will form within the liquid and if the mass of water stays constant this will cause the steam water mixture level to rise. As the rate of steaming in the steam generator increases the ratio of steam to liquid in the steam generator will increase and cause an even higher level although the mass of 'water' in the steam generator will not have changed.

This increase of steam generator level is programmed into the control system. The level setpoint in the steam generator increases linearly with steam flow until maximum steam generator level is achieved at 100% steam flow.

The effect of rapidly lowering the pressure of saturated liquid may be seen on a temperature/enthalpy diagram.

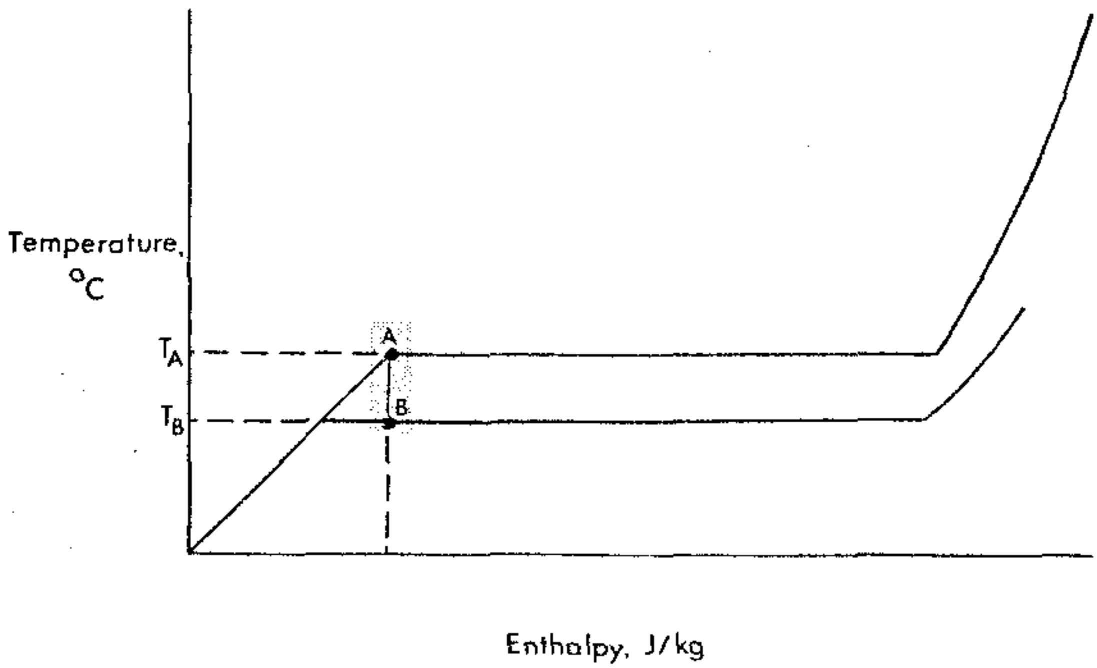

Fig. 2.1

The enthalpy remains constant and as the pressure rapidly falls, the liquid has more heat than is needed for saturation conditions and the excess heat produces vapour. What happens to the level in the steam generator? It rises! You can see this effect if a large steam reject valve or a condenser steam dump valve is open. The steam generator level rises momentarily. If there had been a high level in the steam generator then there would have been a danger of priming the steam lines with liquid from the steam generator. This effect of increased volume due to a sudden decrease in pressure or rise in temperature is called "swell".

The maximum swell effect in the steam generator would occur when there is a large demand in steam flow, eg, an increase in load from 50% to 100% power on a hot turbine. In this case the swell would not cause a problem because the programmed level would only be at the 50% power setpoint and so priming is less probable.

In the event that an abnormally high level occurs in the steam generator, a governor steam valve trip is initiated to prevent liquid being carried into the turbine where massive blade failure could occur.

Look at the following questions and compare your answers with those at the end of the module.

B.2.4

The mass of "water" is kept constant in the steam generator over a wide power range. As the steam flow increases the programmed level in the steam generator also increases. Explain why the programmed level has to increase with steam flow.

B.2.5

Explain why it is undesireable to have liquid enter the steam turbine and state how the probability of this event occurring is reduced.

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The effect of swell is reversed when the pressure in the steam generator is suddenly increased. This may occur with a turbine trip when the steam flow is instantaneously reduced. Any vapour bubbles which exist within the liquid are collapsed and the liquid level falls. This causes the fluid in the steam generator to "shrink". If the steam generator is operating at a low level when the turbine trip occurs, then the resulting shrink may result in a very low steam generator level.

There are three potential problems with a very low steam generator level. First, the level may fall below the sensing point for level control, which is above the top of the tube bundle. This means that the level control program can no longer detect the level - it still operates at minimum level signal.

Secondly, as the water inventory in the steam generator falls the capacity as a heat sink for the reactor is also reduced and this is obviously an undesireable trend.

Thirdly, if the level in the steam generator falls any further the tube bundle will be uncovered and dry out will occur. The dissolved solids existing in the steam generator will "bake out" on the tube surfaces and impede future heat transfer.

The problem of low level is accommodated initially with an alarm which may allow operator action and finally with a reduction of reactor power, either by a setback or a trip depending upon the operating rationale at the station concerned. The effect of rapidly reducing reactor load ensures that the reactor thermal power is more closely matched to the reduced heat sink capacity of the steam generators.

Answer the following questions and compare your answer with the notes at the end of the module.

B.2.6

Explain why the level in the steam generator initially falls on sudden reduction of steam flow.

B.2.7

Explain three potential problems of low steam generator level and how the effect of these problems is reduced in practice.

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There are three signals used for the level control program,

(a) steam flow,
(b) feed flow,
(c) actual level.

The steam flow signal is used to produce a programmed level setpoint for the steam generator which varies linearly from 0% to 100% steam flow.

Control circuits compare steam and feed flows for mismatching, they also compare actual and programmed steam generator levels.

At low flows of steam and feedwater, measurement of flow is unreliable. In addition to this problem any feedwater regulating valve operation has a dramatic effect on the system because the flowrates are so low. One minute there is virtually no flow at all, then a regulating valve cracks open and a great slug of water enters the system.

In this low power/flow condition steam generator level is essentially controlled by the level controller exclusively. Above ~20% flowrate, when the large feedwater regulating valves are in service the level control system can operate with all three elements.

Change of Steam Generator Programmed Level/Power

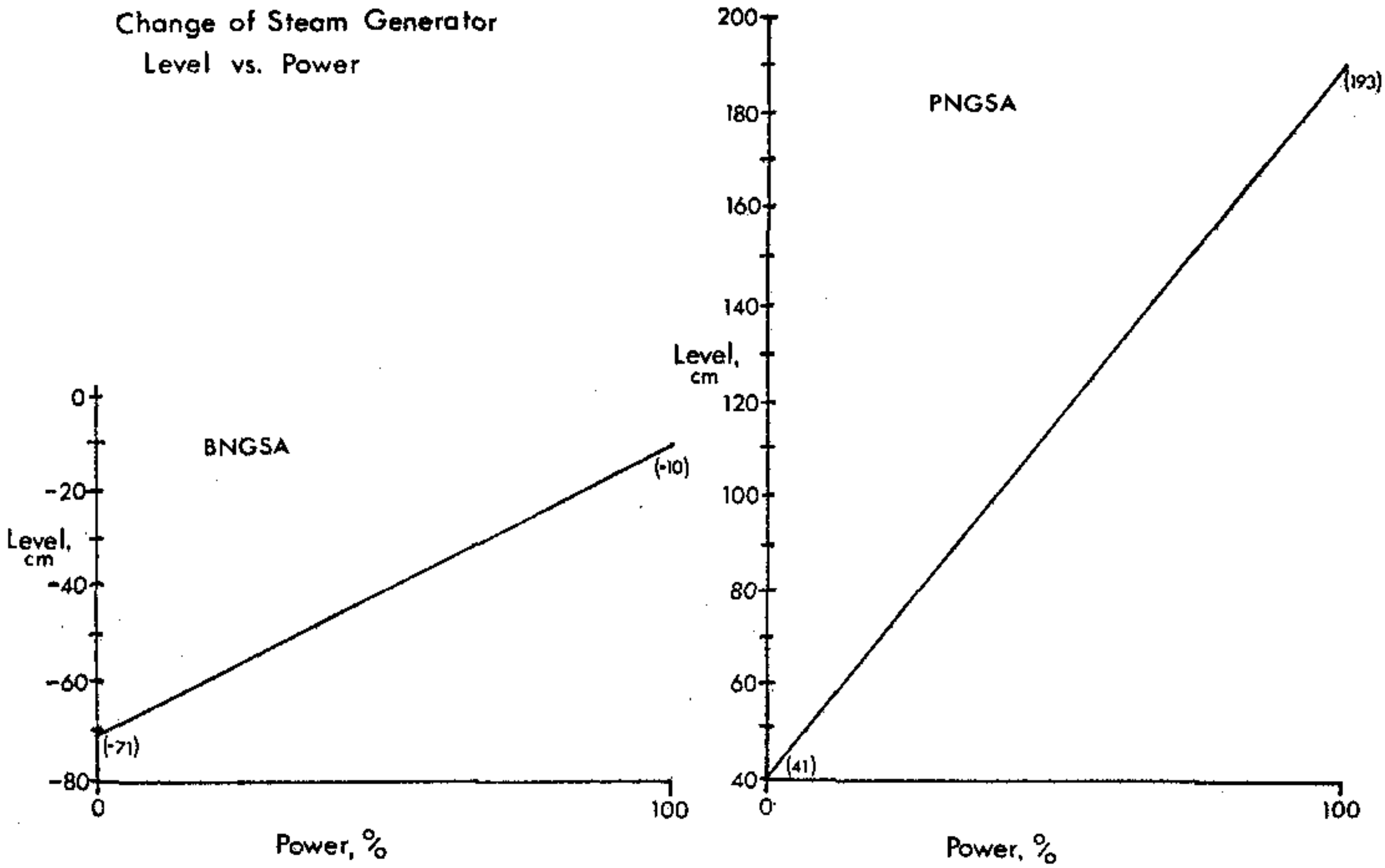

Fig. 2.2

By comparison you can see that the programmed level at Pickering NGS-A changes by 152 cms whilst the programmed level at Bruce NGS-A only changes by 61 cms.

B.2.8

Why do you think this difference exists? Compare your answer with the notes at the end of the module.

B.2.9

State the three elements which are used in a boiler level control program. Explain how level control is effected at low power levels.

B.2.10

The high level alarm has been received on a boiler. What actions can the operator take?

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Boiler Pressure Control

Boiler pressure is used to control the mismatching which may occur between the thermal power produced by the reactor and the thermal power removed from the steam generator by the steam flow.

As we have already discussed, in a saturated steam system either temperature or pressure may be used to represent the same heat quantities. In the Candu system we use pressure because it is so sensitive to changes in the balance of thermal power.

The main heat sink for the reactor is the steam generator. In turn, the steam generator has its own heat sinks, some small, some large, some variable, some fixed.

Steam Turbine

This is the normal consumer of steam from the steam generator. At Pickering NGS-A it is capable of using all the reactor steam. At Bruce NGS-A the situation is complicated by the supply of reactor steam to the Heavy Water Plants.

At Bruce NGS-A the turbine cannot take all the reactor steam and consumes 88% of the total reactor steam if both the reactor and turbine are at full load.

Changes in turbine or reactor power may be made by the BPC program to meet the designed pressure setpoint.

Steam Reject/Discharge Valves

These valves are capable of discharging any steam flow necessary to restore system control. If the turbine is available there is usually an offset before these valves operate, to allow speeder gear operation to have an effect on the steam flow via the GSV.

If the turbine is not available, the offset is removed and these valves operate as soon as the pressure setpoint is exceeded. If the mismatching is large enough for the main reject/discharge valves to operate, then a reactor setback is initiated until the large valves close and equilibrium is restored.

Safety Valves

In the unlikely event that the turbine and/or the reject/discharge valve systems cannot control the pressure excursion, then the steam generator safety valves will allow the excess steam to be vented to atmosphere.

Auxiliaries (D/A, Gland Steam, Steam Air Ejectors)

These loads are relatively fixed and although they may account for up to 10% of the total steam flow, they do not appear as controllable heat sinks from a steam generator pressure viewpoint.

Boiler Blowdown

This is a variable heat sink and may affect the steam generator. However, the flowrate is only 1-2% and as a result has an insignificant effect on boiler pressure.

B.2.11

List the three major heat sinks for the steam generator and state when they are used.

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Boiler Pressure Set Point "At-Power"

In all the BPC programs there is a pressure set-point at various power levels.

At Bruce NGS-A the pressure set point is constant at 4.3 MPa(a).

At Pickering NGS-A the pressure setpoint falls from 5.09 MPa(a) at 0% power to 4 MPa(a) at 100% power.

The rationale for these two situations will be discussed in further detail in Module B.1 "Reactors". At this point this is the set of conditions that have to be met by the steam pressure control programs at each station.

BPC Pressure Setpoint vs. Unit Power

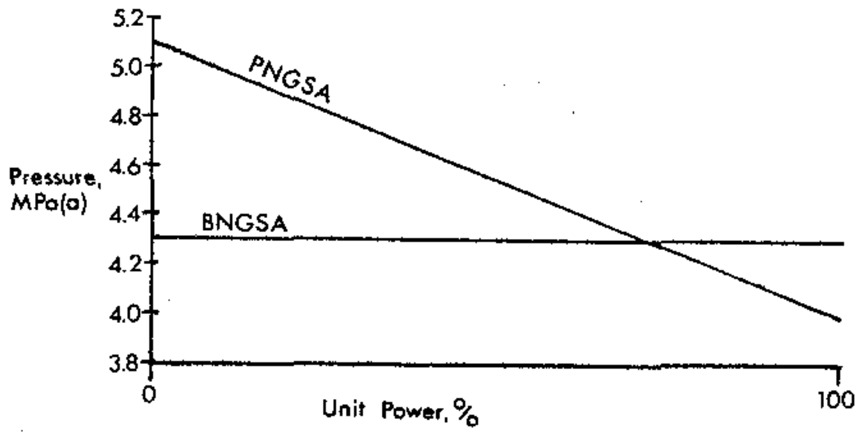

Fig. 2.3

We are examining the pressure of the steam generator. Suppose we want to raise the pressure in the steam generator, how could we do this? The reactor is rejecting heat to the steam generator and the steam generator is rejecting heat via the steam system.

If we wish to raise the pressure in the steam generator we have to produce an imbalance which results in more heat being supplied to the steam generator from the reactor than is being removed from the steam generator via the steam. There are two ways that we could to this:

(a) Raise reactor power.
(b) Decrease steam flow from the boiler.

In practice the method used would depend upon the mode of control.

On the other hand, if we wanted to lower the steam generator pressure, there are two actions that could be taken:

(a) Reduce reactor power.

(b) Increase steam flow from the steam generator.

Reactor Leading Mode

In this mode, the reactor power is kept constant and the steam flow from the steam generator is varied to meet the programmed BPC setpoint pressure for the reactor power. This mode is used at Pickering NGS-A as the 'normal' operating mode and is used at Bruce NGS-A for low power operation and for abnormal conditions.

Reactor Lagging Mode

In this mode, the generator load is kept constant and the reactor is controlled to maintain the boiler pressure setpoint. This is the 'normal' mode used at Bruce NGS-A.

Boiler Pressure Control - Reactor Leading

In this mode, the reactor power is changed to the new value and the BPC program makes sure that the rest of the system follows.

Suppose we want to raise unit power. Initially we can change demanded reactor power and produce more heat. There will now be more heat rejected to the steam generator than is being removed by the steam. As a result the pressure will rise in the steam generator. The BPC program sees the rise in pressure and opens the governor steam valves to allow more steam to flow out of the steam generator into the steam turbine, thereby reducing the steam generator pressure back to the programmed setpoint for that reactor power.

The turbine provides the primary heat sink for the steam generator. In the event that the turbine could not reduce the steam generator pressure, then the secondary heat sink would be used, ie, Steam Reject Valves (SRV's).

If the speeder gear is not under BPC control and the mismatch causes the steam pressure to rise above the pressure setpoint the small SRV's will open. If this does not reduce the steam pressure then two events will follow:

(a) the large SRV's will open to reduce the steam generator pressure.

(b) the reactor power will be reduced until the large SRV's shut, thereby quickly reducing the mismatch in power.

If the unit power is to be reduced, a reduced demanded reactor power is input. The steam pressure starts to fall as now more heat is being removed from the steam generator than is being supplied by the reactor.

The BPC program monitors the falling steam generator pressure and reduces the steam flow into the steam turbine via the GSV's to restore the setpoint pressure.

B.2.12

Describe how a rising boiler pressure signal would be handled with a "reactor leading" mode, at power, when the speeder gear is not controlled by the BPC program.

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Boiler Pressure Control - Reactor Lagging

In this mode the generator power is kept constant and the reactor power setpoint is adjusted to maintain the pressure setpoint.

Suppose we wanted to raise unit power. Initially an increase in demanded power would result in an opening of the GSV's which would result in a lowering of the steam generator pressure because more heat is being removed with the steam than is being supplied by the reactor. The BPC program responds to the falling boiler pressure by raising the reactor power setpoint until the boiler pressure returns to the programmed value.

As already mentioned, this mode applied only at Bruce NGS-A. In extreme cases where the reactor manoeuvring cannot control the pressure, the BPC program reverts to reactor leading. In the high pressure situation atmospheric steam discharge valves relieve the excess pressure. If the boiler pressure error is too large because of low pressure, a slow speeder runback is initiated until boiler pressure is restored.

B.2.13

Describe how a falling boiler pressure signal would be handled with a "reactor lagging" mode at power.

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Warm Up Mode

In this mode the Heat Transport system temperature may be raised by requesting a constant rate of change of boiler setpoint pressure.

The excess steam is vented to atmosphere via the steam reject valves at Pickering NGS-A or the atmospheric steam discharge valves at Bruce NGS-A.

By increasing the pressure in the steam generator the temperature is also increased. A common example is an automobile radiator. (Why increase the radiator pressure? If overheating was a problem raising the pressure may prevent boiling and would increase the heat removal rate from the radiator due to the higher coolant temperature resulting from the higher pressure.)

Cooldown Mode

In the cooldown mode heat has to be removed from the reactor until the reactor can be cooled with shutdown cooling.

If the turbine is available the turbine load can be reduced using the BPC program so that the electrical output reduces with the reduced steam flow available from the steam generator.

It should be noted that as the steam pressure falls, the quality of steam in the turbine is deteriorating and this increasing wetness in the turbine may be a very good reason for not allowing the BPC program to use the turbine all the way down. In this case switching the speeder control to "Manual" would bring the steam reject values into operation.

If the turbine is not available, as in a turbine trip, then steam is rejected either to atmosphere via steam reject valves at Pickering NGS or to the main condenser via condenser steam discharge valves at Bruce NGS-A. This process continues until the temperature of the PHT falls to around 170°C at which point the SRV's are full open and no longer capable of reducing the PHT temperature. It is at this point that the shutdown cooling takes over.

B.2.14

Explain why the BPC program terminates at 170°C when in the 'cooldown' mode.

Cycle Efficiency

As stated in Module B.3.1, we can get best use (ie, most efficiency) from steam when the temperature difference between the steam in the steam generator and the steam in the condenser is at maximum.

If we raise the steam pressure in the steam generator, how does this affect the steam temperature?

Since the water in the steam generator is at saturation conditions, if the pressure of the water is raised the water will boil at a higher temperature. Thus, the temperature of the steam produced will increase - this increases the temperature difference between the steam in the steam generator and that in the condenser. The efficiency of the cycle will increase as well.

There is a limitation on the pressure of the steam generator. As the pressure and temperature of the water/steam system are increased, the temperature difference across the steam generator tubes is decreased and less heat is transferred from the primary heat transport fluid. The temperature of the primary heat transport fluid in the tubes will increase. This will cause the temperature of the primary heat transport fluid in the reactor to increase. Less heat will be transferred through the fuel sheath and the fuel and fuel sheath temperatures will rise.

The limiting temperature of the primary heat transport fluid in the reactor is 290 to 300°C. At this limit, the temperature in the fuel reaches a maximum of 2300°C and the fuel sheath temperature is approximately 350 to 400°C. If the heat transport fluid temperature rises above 300°C, (with no boiling), the maximum fuel temperature approaches the melting point (about 2800°C).

If melting of fuel occurs, fission product gases normally held at the fuel grain boundaries are released, building up high pressures inside the fuel sheath. The fuel sheath temperature is increasing rapidly (and its mechanical strength is decreasing) as the heat transport fluid and fuel temperatures increase. The high pressures on the inside of the fuel sheath will contribute to failure of the sheath which will likely occur in the range of 800 to 1100°C. When sheath failure occurs there will be release of fission products into the primary heat transport system.

Answer the following questions and compare your answers with those at the end of the Module.

B.2.15

How does raising the pressure of the steam generator improve the efficiency of the steam/water cycle?

B.2.16

Explain the limitation (in the CANDU system) on raising the steam generator pressure.

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We have covered the major points concerning the steam generator. You should turn to the objectives and read them carefully. If you feel that you can satisfy these requirements, ask the course/shift manager for the Criterion Test.

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When you have completed the test, ask for the Self Evaluation Sheet and compare your answers.

When you are ready, ask the course/shift manager to review your work. If you identify areas that need further practice, return to the relevant section and then try the test again when you feel you are ready.

When you are both satisfied with your work, have the manager sign off the progress summary sheet and proceed to the final Module, B.1 "Reactor".

Answers

MODULE B.2

STEAM GENERATOR

B.2.1

In a "crash-cool" exercise, the steam is rejected from the steam generator fast enough that the pressure will fall. In this situation, the temperature in the steam generator falls with the pressure. The result of the falling temperature is to increase the temperature difference between the PHT system and the steam generator which increases the rate of heat removal from the reactor and reduces the time for reducing reactor temperature.

B.2.2

The effect of increased thermal resistance means that a higher temperature difference is required to transfer the same amount of heat. This is exactly the same as in the electrical analogy where the voltage applied to a higher resistance has to be increased to transfer the same amount of power through the circuit.

The higher temperature difference can only be produced by an increase in the PHT average temperature. So an increase in the thermal resistance of the steam generator tubes, due to corrosion products and other material contamination, will result in an increase of the average PHT temperature.

B.2.3

Using the steam table, we can compare the specific volume of liquid v_f at 170°C and 250°C using table I,

$$v_f \text{ at } 170^\circ\text{C} = 1.1144\ \ell/\text{kg}$$

$$v_f \text{ at } 250^\circ\text{C} = 1.2513\ \ell/\text{kg}.$$

$$\text{Change in volume} = 1.2513 - 1.1144$$

$$= 0.1369\ \ell/\text{kg}.$$

$$\text{This percentage increase in volume} = (0.1369/1.1144) \times 100$$

$$= \underline{12.3\%}.$$

Obviously there is some increase in level solely due to this expansion effect.

B.2.4

Suppose the steam generator is at operating temperature but producing no steam. At this condition the boiler would be full of liquid containing no vapour bubbles. The level of the liquid would be that corresponding to the programmed level at 0% power.

If the heat input to the steam generator is increased boiling will now occur and vapour bubbles will be produced within the liquid. This will have the effect of "floating" the surface of the liquid to a higher level.

As the rate at which heat is being supplied to the boiler increases, to the maximum, so the generation of vapour bubbles reaches a maximum. At this full power steaming rate the steam generator level reaches its highest value.

Steam is leaving the boiler and the fluid is being replaced by feedwater entering the boiler to maintain a level, programmed to the rate of steaming, to keep the mass of water in the vessel sensibly constant.

At full load approximately 10% of the weight of fluid in the boiler is due to vapour bubbles. These vapour bubbles produce an increase in the total fluid volume of approximately 5 times, when steaming at full power.

B.2.5

Liquid has a high density in relation to vapour. It is also relatively incompressible. This means that when a change of direction is needed with liquid flows at high velocities and large flowrates very large forces can result. Water hammer is an illustration of this effect. The liquid will tend to move in a straight line. Can you imagine a slug of water passing through the high pressure turbine in a straight line? Slugs of water in a steam turbine produce the same type of problem as birds flying into aviation gas turbines.

The blading attempts to change the direction of the liquid flow into the turbine and it is even money at best as to whether the blade is strong enough to withstand the impact or the water breaks the blading and wholesale blade shedding results.

Needless to say the presence of water is to be avoided and this event is anticipated by a high level alarm on the steam generator which may allow some operator action before a high level trip operates the governor steam valves on the turbine to exclude the liquid.

B.2.6

One of the easiest ways of analyzing this effect is to return to the temperature/enthalpy diagram and plot the initial condition and raise the pressure keeping the enthalpy constant.

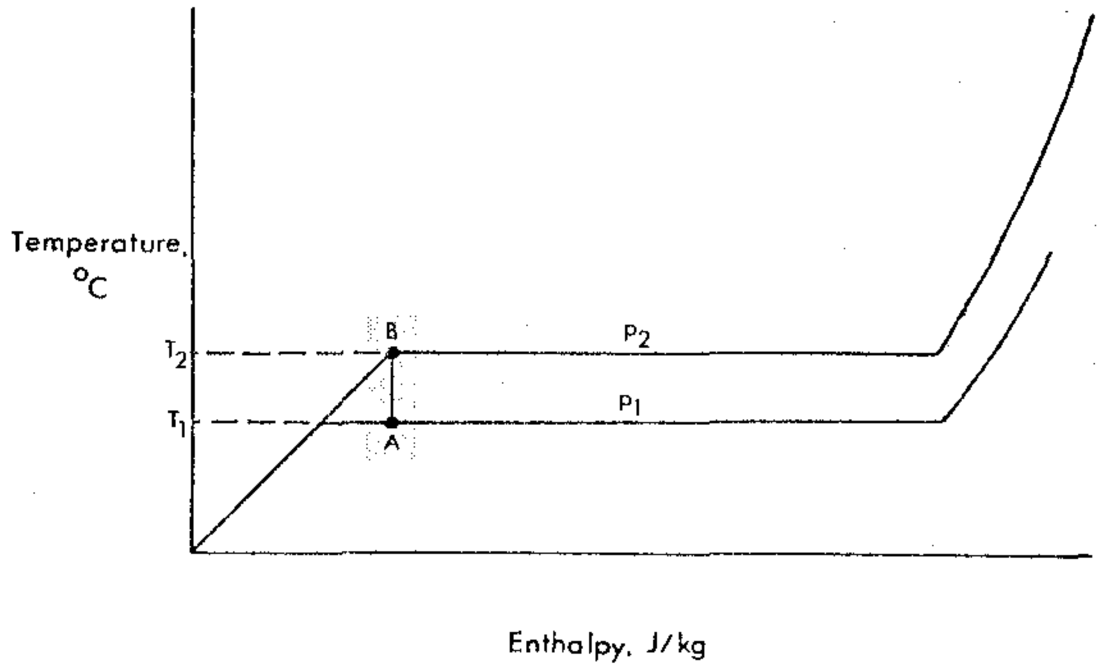

Fig. 2.4

Initially the steam generator has fluid as liquid/vapour mixture at pressure P_1 as shown at point A. When the pressure suddenly increased to P_2 the mixture is now below the saturation temperature corresponding to the higher pressure and the vapour bubbles condense as the latent heat of vapourization is used to raise the liquid to the new saturation temperature.

The condensation process causes the vapour to disappear and the volume shrinks resulting in a reduced steam generator level.

B.2.7

There are basically three problems that arise from a very low steam generator level.

First, as the water inventory in the steam generator is reduced there is less capacity as a heat sink for the reactor. This means that from a control point of view we are moving in a direction where we have more reactor thermal power than we can handle. Not a desireable situation!

Secondly, if the level falls below the low level tapping on the steam generator, the level control program will not recognize this event and actual level measurement will be lost.

Thirdly, if the steam generator level falls below the top of the tube bundle, dry out will occur and dissolved solids existing in the steam generator will "bake out" onto the external tube surfaces and impede future heat transfer.

The probabilities of the above events occurring are reduced by a low level alarm which may allow some operator action. If this is not successful, a significant reduction in reactor power occurs to restore the match of thermal power of the reactor to the reduced heat sink capacity of the steam generator. The reduction of reactor power may be a setback or trip depending upon operating rationale at the specific station.

B.2.8

The whole concept of changing the programmed level with steaming rates revolves around maintaining adequate heat sink for the reactor.

If you don't think about it, it would appear that the Bruce NGS-A reactor which is 60% larger than Pickering NGS-A doesn't require as large a heat sink. This obviously is not the case. There is a large design difference in the steam generators at Bruce NGS-A not the least of which is the common steam drum which is partly full of liquid and therefore presents a much larger capacity than at Pickering NGS-A. This is the primary reason for the smaller change in steam generator level with power, there is more capacity available for the same level change.

B.2.9

The three elements are:

(a) Steam flow,
(b) Feedwater flow,
(c) Actual level.

The steam flow is used to produce the programmed level.

The comparator circuits look at:

Steam/Feedwater flow
Actual/Programmed level.

At low power levels measurement of steam flow and feedwater flow is not very accurate and control of the feedwater flow via the feedwater regulating valves is insensitive. At this point the steam generator level is more easily handled by the level controller alone without the other two elements.

When the steam flow is in excess of 20% and the large feedwater regulating valve is being used, the three elements may be used to monitor steam generator level.

B.2.10

Every station is going to have different systems and constraints. As a result we can only examine the concepts and then see how the concepts are applied in the operating manuals.

The question does not state whether the boiler is associated with a bank of boilers, furthermore it does not state whether all the boilers have the same high level.

We must make some assumptions. We'll assume that the boiler is in a bank of boilers and is the only boiler with a high level.

At low loads it is common for different boilers to have different steaming rates due to physical positions within the system. It is important to identify the boiler which has the highest steaming rate and ensure that the feedwater trim/isolating valves are left in the full open position.

The high level in the boiler should be reduced by slightly opening the trim valves on the remaining boilers. The objective is to have all the boiler levels at sensibly the same value.

If after adjusting trim valves the levels overall remain high, then this situation may be corrected by reducing the setpoint of the feedwater control valve controller.

This situation is most likely either at low loads where small changes in actual flowrates are going to have a very significant effect, or when reactor power distribution to the boilers is changed by changes in reactor zonal power production.

If there is a danger of boiler high level tripping the turbine then the boiler blowdown valves may be opened to try and prevent this happening.

B.2.11

The three main heat sinks for the steam generator are:

(a) Steam Turbine
(b) Steam Rejection System
(c) Boiler Steam Safety Valves.

Steam Turbine

This is the normal heat sink and is used as a heat sink when the turbine steam flow is used to control the boiler steam pressure.

Steam Rejection System

This is used as the second heat sink and may reject steam to atmosphere or the condenser depending upon the station in question. This system is used if the turbine is not available to remove the excess steam. In this case the offset is removed and the SRV's operate as soon as the pressure setpoint is exceeded.

Boiler Safety Valves

In the unlikely event that neither the turbine nor the SRV's can restore the over pressure the boiler safety valves will lift to protect the steam generator from overpressure.

B.2.12

The "reactor-leading" mode is the 'normal' mode for Pickering NGS-A which means that the reactor power will stay constant whilst the steam flow is adjusted to maintain the pressure setpoint.

If the turbine speeder gear is not controlled by the BPC program then no change in steam flow to the turbine can occur and steam flow from the steam generators will be achieved by opening of the reject steam valves.

The offset which normally applies to the steam reject valves, when the turbine is available to the BPC program, is removed. As soon as the boiler pressure exceeds the setpoint pressure the steam reject valves will start to open.

If the over pressure is such that the large reject valves are needed, then a reactor setback will be initiated to reduce the time taken to restore control.

The reactor setback would stop when the large steam reject valves closed. If this did not happen the reactor would reduce power to 2% FLP.

B.2.13

In the 'reactor lagging' mode of operation the variable power is associated with the reactor. If the steam pressure started to fall below the setpoint pressure the demanded reactor power would be increased to restore the steam generator pressure.

In the event that the steam pressure continued to fall the unit control would change and initiate a slow speeder gear runback until the steam pressure was restored.

B.2.14

The BPC program relies upon being able to change the steam flow from the boiler to change the boiler pressure.

As the steam pressure in the boiler drops the volume of steam increases. For example at 250°C, 1 kg of dry steam has a volume of 50 liters. As the temperature and pressure fall, this volume increases. At 130°C the volume has now increased to 668 liters per kg which is an increase of more than 13 times.

The effect of this increasing steam volume causes the SRV's to open until they reach a point where they are fully open and can no longer reduce the pressure in the steam generator.

This happens at around 170°C. As a result, this is the termination point of cooldown using BPC. Further cooling of the PHT system will take place using the shutdown cooling circuits.

B.2.15

As the pressure in the steam generator is raised, the water boils at a higher temperature, ie, the steam temperature increases. This has the effect of increasing the temperature difference between the steam in the steam generator and that in the condenser. This increased temperature difference means there is more work available in the turbine, which increases the cycle efficiency.

B.2.16

The fuel limits the operating pressure and temperature of the steam generator. The fuel is a ceramic which has very poor heat transfer characteristics. With centre fuel temperature about 2300°C, the sheath temperature is only 350 to 400°C. Allowing for heat transfer from the fuel to the D_2O and heat transfer from the D_2O to the light water in the steam generator, the operating temperature in the steam generator is around 250°C.

If the centre fuel temperature reaches the melting point (at about 2800°C), release of fission product gases from the fuel may contribute to sheathing failure and escape of fission products into the primary heat transport system.

Thus the limiting fuel temperature is 2300°C (allowing a safety margin), which means the maximum pressure available in the steam generator is the saturation pressure corresponding to 250°C, ie, about 4 MPa(a).

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