COURSE 225

HEAT & THERMODYNAMICS

MODULE 8

REACTOR

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Heat & Thermodynamics

MODULE 8

REACTOR

Course Objectives

The student will be able to:

1. State the parameter which is monitored to ensure fuel operating limits are not exceeded in non-boiling channels and briefly explain why this parameter cannot be used to ensure safe fuel operation for boiling channels.

2. Briefly describe two methods that are used to monitor that heat production in boiling channels is kept within specified limits.

3. Briefly explain how fuel channel blockage can be detected and state the major problem resulting from channel blockage.

4. Briefly explain four major reasons for a high HT system pressure and three major reasons for a low HT system pressure.

5. Briefly explain how a loss of heat transport coolant may be detected.

6. Briefly explain the immediate and longer term effects of losing feedwater supply to the steam generators.

7. Briefly explain how a loss of coolant accident would produce fuel failures assuming no protective action occurred.

8. Briefly explain how the temperature and quality of the HT coolant change when bulk boiling occurs.

9. Briefly explain why crash cooling is necessary for a LOCA which results in a very low rate of pressure decrease in the heat transport system.

10. Explain how HT thermosyphoning is established and how the reactor outlet header temperature is used as a datum for the control of thermosyphoning.

REACTOR

Introduction

The reactor is the first step in our energy transfer process to produce electricity. The control of the reactor is extremely complex in that it is so sensitive to changes in dependent systems, eg, the moderator system, the primary heat transport system and the steam system. It is virtually impossible to discuss one system without referring to another.

The Heat Transport (HT) system has three sources of heat input:

(a) Fission heat.
(b) Decay heat from fission products.
(c) HT pump heat.

When at power the fission heat is, by far, the largest of these three terms (~93% FP). The maximum heat from decay of fission products is, typically, only 6% FP. At low power, the pump heat input to the HT system becomes significant (~1% FP).

The main purpose of the HT system is to remove the heat from the three sources ie, decay and fission heat in the fuel bundles and the pump heat. With the reactor at power, this is done by circulating the heat transport fluid through the steam generators. In the event that the steam generators are not available as a heat sink for the heat transport system, the reactor is shutdown because there is no backup heat sink capable of removing full reactor power.

When the reactor is in the shutdown state with the heat transport temperature below about 170°C, the shutdown cooling system removes the heat which is much less because it is only the decay heat of fission products and HT pump heat.

<u>Q8.1</u> State the three sources of heat to the primary heat transport system and the two <u>main heat exchanger processes</u> which are used to remove this heat. Compare your answer with the notes at the end of the module.

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Fuel Bundle and Channel Heat Transfer

Before we look at temperature and pressure effects in the HT system, let us have a look at a fuel channel and examine more closely some of the conditions which exist.

As a result of design considerations (discussed more fully in Materials 228 or Reactor, Boilers and Auxiliaries 233), uranium dioxide (UO_2) was chosen as the fuel for CANDU reactors. As UO_2 is a ceramic material, its thermal conductivity is very low and the pellet core temperature is therefore much higher than the surface temperature. Fortunately, UO_2 has a high melting point (approximately 2800°C) and can tolerate relatively high temperatures at the pellet core.

The temperature profile of a fuel element may be seen from Figure 1.

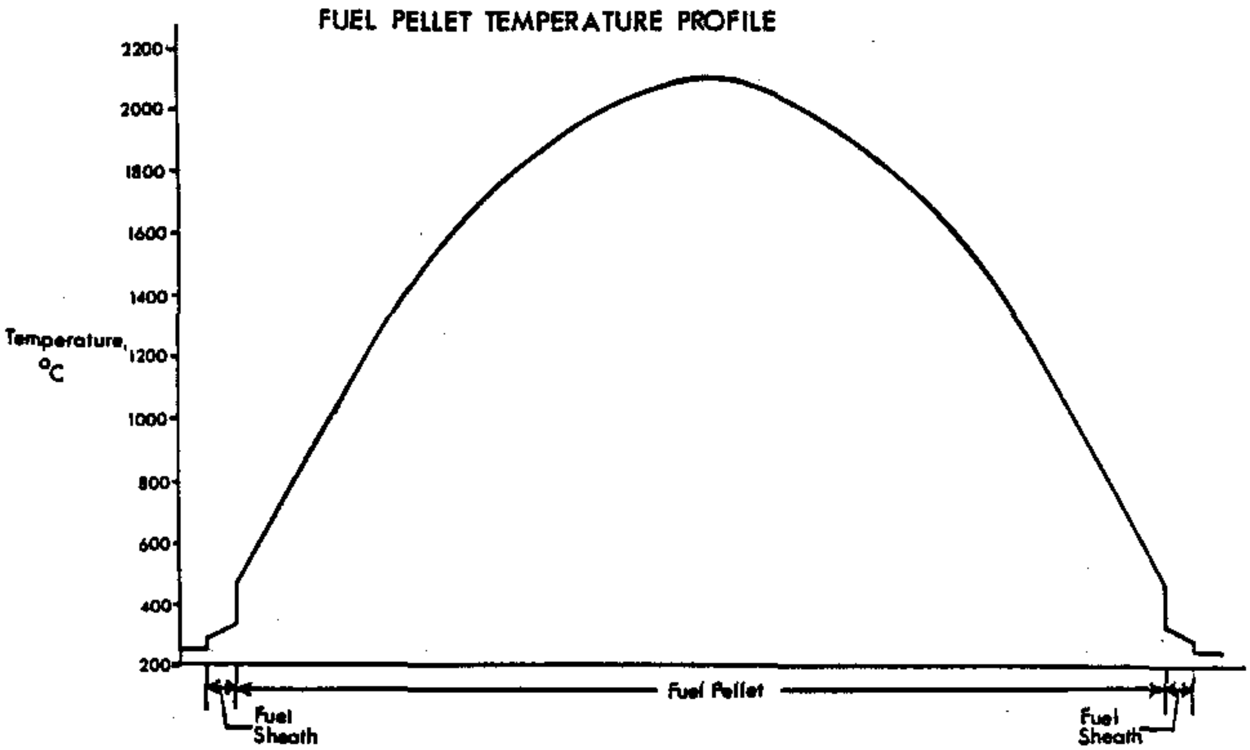

Figure 1
Fuel Pellet Temperature Profile

From Figure 1, you can see how effective the thermal resistance in the fuel element becomes. In a distance of 7 mm, which is a little over 1/4", the temperature has dropped from 2100°C in the centre of the fuel element to around 500°C at the inner surface of the sheath. The outer surface of the sheath is at a maximum temperature of about 305 to 326 °C dependent on the specific power plant.

Bruce NGS-A and -B, Darlington and CANDU 600 reactors have smaller diameter fuel elements allowing the higher sheath temperature of about 326° C. The maximum centre line temperature of the fuel pellets is typically lower than that shown in Figure 1.

We can gather from the discussion so far that a fuel element/bundle has temperature limitations. In fact, the metallic fuel sheath (Zircaloy 4) has both a temperature and strain limit which are set to maintain structural integrity of the sheath. The UO_2 fuel pellet has only a temperature limit which must not be exceeded if excessive release of fission products is to be avoided. These temperature limitations result in the setting of bundle power limits and subsequently channel power limits to ensure that the fuel is not subjected to excessive temperatures.

There are basically two ways of approaching the temperature/power limitations:

(a) Increased heat production.

(b) Impaired cooling of fuel.

Increased Heat Production

How do we know what is happening to the fuel bundles in a particular channel? How do we know if one bundle is being overpowered or being subjected to excessive temperatures? The short answer to both these questions is that we do not know directly what is happening with an individual bundle.

The neutron flux distribution along a fuel channel is a familiar shape and is shown in Figure 2. It represents the amount of power being produced at a point in the channel and we can see that the bundles in the centre of the channel are subjected to higher neutron flux than those bundles in the outer sections. This means these central bundles are operating at a higher power level and producing more heat.

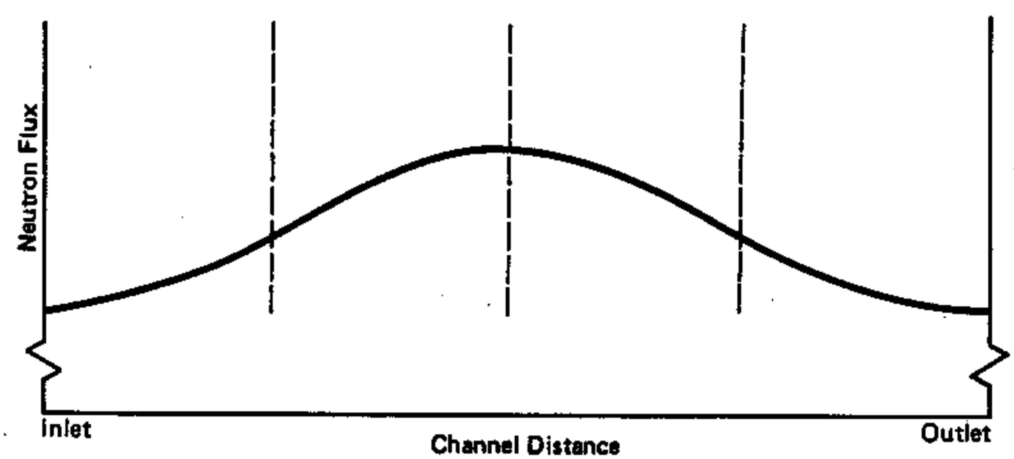

Figure 2
Neutron Flux vs Core Channel Distance in Nonboiling Fuel Channel

Figure 3 shows the coolant temperature along the channels as a result of the flux distribution illustrated in Figure 3.

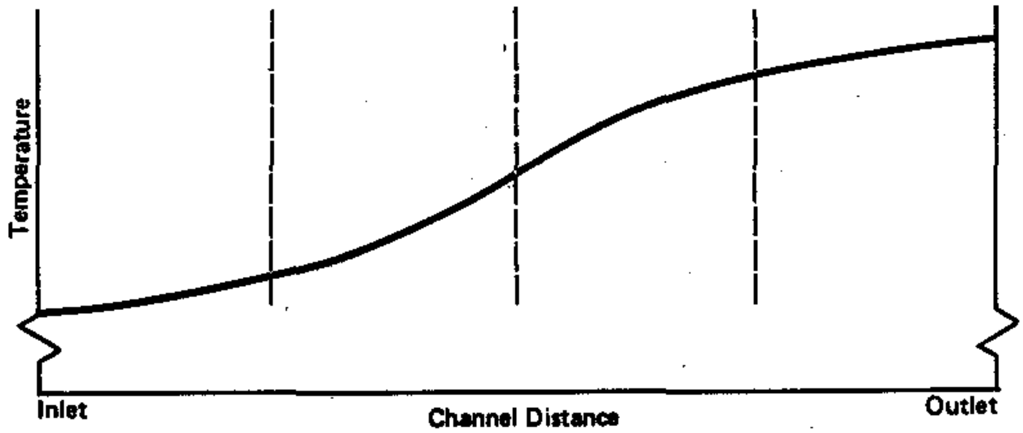

Figure 3
Temperature vs Core Channel Distance in Non-boiling Fuel Channel

Figures 2 and 3 represent typical neutron flux and temperature profiles for a non-boiling channel. Variations in flux resulting from reactivity device movements, local transient xenon effects, fuelling direction, etc, will affect the neutron flux profile and consequently the temperature profile. In addition, the distribution of thermal power along a channel may not correspond exactly to the flux shape due to variations in fuel burn up and decay heat contributions.

Our main concern is that the fuel bundles which occupy the central to end positions in the channel are not being subjected to conditions beyond the fuel operating limits.

If conditions exist such that neutron flux levels are higher at any point along the channel, the heat production in the bundle increases at that point leading to increased heat transfer to the coolant. If the coolant is not boiling at this point, then its temperature will rise. If the coolant is boiling, then vapour production will increase. Both of these conditions may lead to excessive boiling and possible dryout towards the channel outlet. As previously discussed (Module 1), dryout is a dangerous condition because it may *lead to a breach of the fuel and fuel sheath integrity.*

How do we determine whether heat production is within specified limits?

In the case of a non-boiling channel, we monitor the temperature rise across the channel as the most effective method of ensuring bundle power and channel power are kept within specified (license) limits.

The power of individual bundles is not measured but can be estimated because we know the channel's thermal power output (mass flow rate x specific heat x temperature rise) and the flux shape along the channel. The channel thermal power, which can also be considered as the sum of the bundle powers, is directly related to the temperature rise across the channel. A maximum allowable temperature rise is set which is equal to the point at which the highest powered bundles approach their operating limits.

In the case of a boiling channel, monitoring the channel temperature rise does not ensure that there is only limited boiling and proper cooling of the fuel. This is because the coolant temperature at the channel outlet is equal to the saturation temperature corresponding to the local pressure. Regardless of the amount of boiling, this temperature remains constant as long as the outlet pressure is constant and there is still some liquid present. (This also precludes the presence of superheated steam.)

For a boiling channel, we monitor the amount of steam produced in the channel to ensure there is sufficient liquid present to maintain adequate fuel cooling. This information can be determined by either of the methods described below.

(a) Using a group of specially selected channels (called FINCHs) which have been fully instrumented, volumetric flow rates for channel inlet and outlet can be compared.

If there is no boiling, the volumetric flow rates will be equal and if there is boiling, the outlet flow rate will exceed the inlet flow rate. The difference allows us to calculate the amount (percentage) of steam present at the channel outlet.

Predictions of steam quality in channels other than FINCHs can be made (with the aid of a computer program) from FINCH data and a knowledge of flux shape in the other channels.

(b) Using a combination of flux shape monitoring and bulk power measurements.

A representative flux map of the core is prepared with the aid of computer simulations and the measurements of a large number of strategically placed, self-powered vanadium detectors. Bulk thermal power is determined by measuring heat production on the secondary side (a combination of boiler steam and feedwater flows and boiler temperature measurement).

Flux mapping in conjunction with bulk power measurements (both thermal and neutronic) are used to help detect slowly developing local high power conditions such as bundle or channel overpowering.

Q8.2 Briefly explain how channel outlet temperature is used to monitor channel/bundle power limits in non-boiling fuel channels. Why is this parameter not useful for monitoring limits in boiling channels?

Q8.3 Briefly explain two methods used to monitor steam quality and ensure adequate fuel cooling in boiling channels.

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Impaired Cooling of Fuel

At this point we will only deal with approaching the temperature/power limitations by reduced coolant flow. The situation resulting from reduced coolant pressure is covered later in this module when covering HT pressure control.

A measured increase in fuel channel temperature rise may not be due to an increase in power, it could result from reduced coolant flow, ie, a channel blockage. Let us consider what happens when there is a reduction in channel mass flow rate while channel power and channel inlet temperature remain constant.

Channel power is the product of the mass flow rate and the change in enthalpy occurring across the channel, ie,

$$\text{Channel Power} = \dot{m}\,(h_{out} - h_{in})$$

Using this equation and conditions identified let us see what this produces.

Power is constant.

Enthalpy of coolant into the channel is constant because the channel inlet temperature is constant.

Mass flow rate is reduced.

$$\underset{\text{constant}}{\text{Channel Power}} = \underset{\downarrow}{\dot{m}}\;(\overset{\uparrow}{h}_{out} - \underset{\text{constant}}{h_{in}})$$

For the equation to balance, the enthalpy of the coolant leaving the channel must rise. The only way this can occur is for the reduced coolant flow to pick up the same amount of heat, ie, channel outlet temperature rises.

Q8.4 In the event that a channel blockage occurs, the enthalpy of the coolant leaving the channel rises with the channel power remaining sensibly constant. Explain why the enthalpy of the coolant leaving the channel rises.

B8.5 A fuel channel is operating normally with the following conditions:

Channel outlet temperature 296°C.

Channel outlet pressure 8.47 MPa(a), corresponding saturation temperature 299°C.

The fuel channel becomes partially blocked and the channel power remains constant. Explain the change in channel outlet temperature that would occur as the channel outlet enthalpy rises.

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As we have already seen, the channel power with constant mass flow rate, is proportional to the channel ΔT, provided no boiling occurs in the channel.

If the outlet and inlet temperatures are equal, then there is no temperature difference (ΔT) and reactor power is essentially zero. As the power is increased, the channel ΔT increases to a maximum at full power of 40° to 55°C, depending on the station.

There are also some significant differences in the method used to measure ΔT across the channel in different stations.

At some stations (eg, PNGS-A and -B), the average HT temperature is kept sensibly constant, rising only a few degrees centigrade over the whole power range. This minimizes shrink/swell in the HT system caused by power manoeuvres and means the HT pressurizing system does not require a pressurizer.

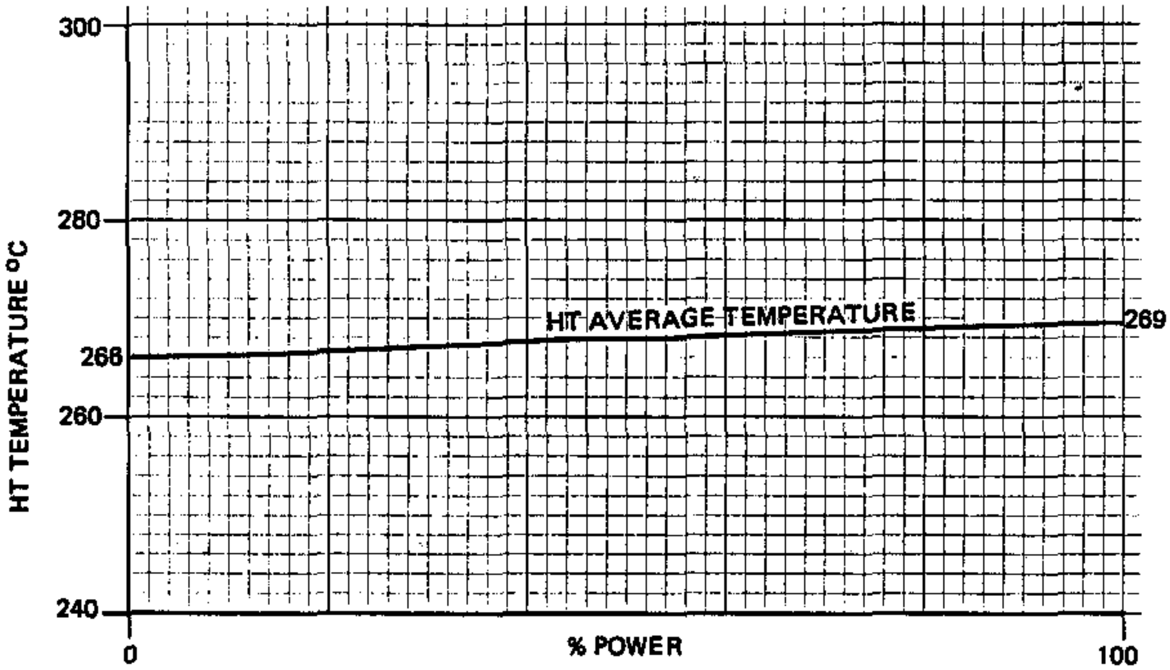

Figure 4
HT Temperature vs % Full Power

Figure 4 represents a HT system where the HT system temperature remains relatively constant over the power range.

B8.6 The steam generator and heat transport systems are fully warmed up with the reactor at the zero power level. What pressure and temperature would you expect to find in the steam generator in the example illustrated in Figure 4?

B8.7 In order to transfer heat from the HT D_2O to the H_2O in the steam generator, there has to be a temperature difference. How would you expect this temperature difference between the heat transport system and the steam generator to change with unit power increasing from 0% to 100% in the example illustrated in Figure 4?

Check your answers with the notes at the end of the module.

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In other stations, eg, BNGS-A and -B, Darlington NGS, where a pressurizer is part of the HT pressurizing system the situation between the HT system and the steam generator is reversed. The pressure in the steam generator is kept relatively constant and the HT average temperature rises as reactor power increases.

B8.8 In a system with a pressurizer, the steam generator pressure is kept constant at 4.25 MPa(a). What is the heat transport average temperature when the unit is at zero power hot.

B8.9 In question Q8.8 how would you expect the heat transport average temperature to change with power? How would this be reflected in terms of the channel outlet and inlet temperatures? Assume that the channel ΔT at full power is 53°C.

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Heat Transport Pressure Control

The heat transport pressure is extremely sensitive to changing conditions within the system and has to be controlled within design limits for safe reactor operation.

There are basically two designs of HT circuit. The 'solid' system (at PNGS 'A' and 'B') has no vapour space and the HT system pressure is very sensitive to changes in fluid volume. This design uses a feed and bleed system for controlling the pressure of the HT system, ie, inventory transfer to and from the HT system.

The second design (at Bruce and Darlington) uses a pressurizer which contains a large volume of D_2O vapour that expands when the liquid volume in the HT decreases and is compressed when liquid volume increases. This arrangement is very much less sensitive to the changes in HT fluid volume when controlling pressure.

In a 'solid' system, the change of pressure due to the change of volume, as a result of leakage or temperature change, is large when compared to a pressurizer system.

A high pressure in the heat transport system may cause over pressure of the heat transport circuit which will result in a reactor setback or trip to safeguard the heat transport circuit.

A high heat transport pressure may be caused by:

(a) A large thermal power mismatch in which the reactor power exceeds the power capacity of the heat sink, eg, boilers causing an increase in average temperature.

(b) A loss of, or impairment in, HT coolant flow, causing an increase in channel ΔT and hence average HT temperature.

(c) A malfunction in the pressure control system allowing an uncontrolled increase in pressure.

(d) A loss of feedwater to the steam generator (boiler).

The immediate effect of losing the feedwater is to reduce the heat transferred by approximately 17% due to the loss of sensible heat required to raise the feedwater temperature from 175°C to 250°C. As a result, the HT system temperature immediately starts to rise and the liquid volume expands, and HT pressure rises.

If power is not reduced, boiler level would fall until the tubes are uncovered and the heat transfer would be further impaired.

In this situation, the primary heat sink for the reactor is significantly reduced and the reactor must be shut down quickly and alternate heat sinks placed in service (eg, shutdown cooling, maintenance cooling).

This situation represents a large mismatch in thermal power.

<u>08.10</u> Explain the effects of losing feedwater to the steam generators.

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A low pressure in the heat transport system may be caused by:

(a) Large mismatch in thermal power with the steam generator removing more heat than is being produced by the reactor. This causes the HT fluid to reduce its volume due to the drop in temperature.

(b) A loss of coolant from the HT circuit.

(c) A malfunction in the pressure control system allowing an uncontrolled decrease in pressure.

In all cases, the rate of volume reduction may be greater than the make-up from the pressurizing system and the HT system pressure will fall as a result. For a system with a pressurizer, the intent of the design is to handle power changes required for normal regulation, about 1%/s or less. The system will not keep up with pressure reductions equivalent to faster rates.

A low pressure in the HT system may produce the following problems:

(a) There is a minimum value of pressure for the HT pump suctions to avoid cavitation. If this pressure is reached, a reduction in coolant flow would impair fuel cooling and if it lasts long enough, pump damage could occur.

(b) As the pressure falls, the HT fluid has more heat than it needs to produce saturated liquid at the lower pressure. In this event, the excess heat is used as latent heat to produce vapour. If excessive vapour is produced, then the heat transfer from the fuel bundles drops dramatically and fuel sheath failure may occur.

Q8.11 State four possible causes of high HT pressure.

Q8.12 State two problems associated with a low heat transport pressure.

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The control of pressure in the heat transport system depends upon how the average heat transport system temperature is changing together with the effect of any additions or subtractions of coolant from the HT system. Needless to say, the systems at each station are different.

Systems Using Feed and Bleed

At PNGS-A/B, the major benefit of having the heat transport average *temperature sensibly constant is that there are no great changes in* HT coolant volume due to temperature effects. In addition, the reactor is designed to have no boiling occur in the fuel channels.

Under normal operation, the pressure variations are relatively small and are accommodated using a feed and bleed system.

Bleed flow is taken from the heat transport pump suction headers. This flow tends to reduce the HT pressure. Pressurizing pumps return the feed to the HT system, thus tending to raise the pressure. The inventory changes due to shrink and swell effects of the heat transport coolant are accommodated by the D_2O storage tank, which also provides the suction for the HT pressurizing pumps. Under steady state conditions, there is a balance between the feed and bleed to provide constant pressure.

The pressure relief valves release heat transport D_2O into the bleed condenser.

In the event of a problem with the bleed condenser that results in high pressure within the bleed condenser itself, relief valves are installed which operate and cause heat transport D_2O to be discharged to the boiler room sumps.

Systems Using a Pressurizer

At BNGS-A/B or Darlington NGS, there is a considerable rise in the average heat transport coolant temperature for the whole reactor (for example at BNGS-A, from 254°C to around 281°C). This temperature rise will result in an increase of heat transport D_2O volume of approximately 5%, approximately 17 m^3.

The changes of fluid volume that occur in the heat transport system with power are much larger than at PNGS-A/B and the technique used to control system pressure is different.

The pressure is controlled by a pressurizer which acts as a cushion on the HT system and absorbs pressure transients. It is similar to a conventional steam drum, having a steam space and a liquid level, and has sufficient capacity to keep the HT pressure and inventory within the predetermined limits for any normal reactor power manoeuvring.

In normal operation, the HT system pressure is determined by the vapour pressure that exists in the pressurizer. If the HT pressure rises, steam bleed valves open on the pressurizer to relieve the vapour pressure and thereby reduce the HT pressure. The steam from the pressurizer is directed into the bleed condenser.

In the event of a low HT pressure, there will be a correspondingly low vapour pressure in the pressurizer. In this case, there are electric heaters which heat the D_2O and produce steam in the pressurizer which increases the pressure in the pressurizer and the heat transport system.

Q8.13 Briefly explain how the heat transport fluid volume changes, when hot, from 0% to 100% power level at PNGS-A and BNGS-A.

Q8.14 Briefly explain how the heat transport system pressure is controlled at power at PNGS-A and BNGS-A.

Check your answers with the notes at the end of the module.

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Pressure Increase in Heat Transport System

Suppose there is a large mismatch in thermal power, with the reactor input thermal power exceeding the thermal power being removed via the boilers. This imbalance will increase the average heat transport temperature resulting in an increase in volume of the HT fluid. HT pressure would also increase, although this increase would be offset by the action of the HT pressure control system.

In a system with a pressurizer (eg, Bruce and Darlington), the D_2O level in the pressurizer will increase significantly and the reactor control system response is, on high level, to initiate a reactor setback in an attempt to restore thermal power balance.

Note that high pressurizer level does not always signify high HT pressure. Abnormally low pressure in the pressurizer, eg, relief valve stuck open (as happened at Three Mile Island), would cause it to fill with coolant even if HT system pressure were low or normal.

For feed and bleed systems, the increase in volume will result in a significant increase in bleed condenser level and the reactor control system response is to initiate a reactor setback on high bleed condenser level in an attempt to restore thermal power balance.

Q8.15 (i) Explain how the pressurizer level could increase due to a thermal power mismatch and the likely response of the reactor control system.

(ii) Explain how the bleed condenser level could increase (in a feed and bleed pressure controlled system), due to a thermal power mismatch and the likely response of the reactor control system.

Q8.16 Describe the possible consequences of a thermal power mismatch where the heat sink exceeds the reactor power.

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Pressure Reduction in Heat Transport System

We have looked at the protection that is designed to accommodate high pressures in the HT system.

Low pressures in the HT system could be indicative of any of the following situations:

(a) The inadvertent opening of a large steam reject/discharge valve resulting in a large mismatch in thermal power between the reactor and the steam generator.

(b) A faulty control system allowing an uncontrolled decrease in pressure.

(c) LOCA

Suppose the HT system was pressurized at 8.00 MPa(a) and the HT temperature at this pressure was 270°C.

How would you show the condition on a temperature/enthalpy diagram?

Q8.17 Sketch a temperature/enthalpy diagram to show heat transport fluid at 270°C and 8.00 MPa(a). What is the state of the heat transport fluid? (Use H_2O steam tables.)

Check your answer with the notes at the end of the module.

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Now, suppose we start to reduce the heat transport pressure by bleeding off some liquid whilst the temperature remains at 270°C.

Q8.18 Explain what happens when the heat transport pressure reaches and then falls below 5.5 MPa(a) when the initial temperature of the D_2O is 270°C.

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Producing a large quantity of vapour in the HT system, such as occurs in a LOCA, results in several problems.

In reactivity terms, the presence of steam (vapour) forms a void (no D_2O liquid) with a consequent local reduction in neutron moderation (and absorption). For all our reactors, there is a positive reactivity effect associated with voids, which will cause reactor power to increase followed by subsequent action by the reactor regulating system or if overwhelmed, by the safety shutdown systems neutronic trips.

The most serious effect is on the heat transfer mechanism that is used to cool the fuel. In the channel, the boiling or production of vapour starts where the temperature of the fluid is highest and the pressure is lowest, ie, at the outlet of the fuel channel. The highest HT fluid temperatures occur at the fuel bundle sheathing.

Remember, in Module 1 we learned that heat removal from the fuel elements was by forced convection. A small amount of controlled boiling improved heat transfer through the vigorous action created by the vapour bubbles leaving the fuel sheath surface. However, excessive boiling led to formation of a vapour film on the sheath surface (dry out) and greatly reduced heat transfer.

The effect of this reduced heat transfer causes the temperature of the fuel elements to rise. As a result, the fuel sheath temperatures become higher.

The major problem is that in this situation, the fuel sheath temperature starts to rise above the normal 350° to 400°C. The Zircaloy 4 sheath loses considerable strength as its temperature rises above normal values. In addition, the already weakened sheath has increased stress imposed by the thermal expansion of the fuel and the increased internal pressure of fission product gases in the fuel. If fuel should melt there will be additional stress due to the volumetric expansion on melting. There is also a danger of molten fuel burning through the sheath on contact as its temperature is above the sheath melting point.

Before the melting point is reached, sheath failure will occur (due to expansion of the pellet); probably in the range 800°C to 1100°C, and the release of fission products into the HT circuit will occur.

The failure mechanism is accelerated by the release of fission product gases from the fuel grain boundaries at the higher temperatures which create a high pressure inside the fuel sheath.

Q8.19 Explain why excessive coolant boiling is undesirable in the reactor.

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Boiling in Fuel Channels not Designed to Boil

Boiling in the fuel channel may occur when the channel flow is reduced. If this only applies to a single channel as would occur due to channel blockage, then the low flow trip will not be effective. If the channel does not have flow monitoring, then there will be no direct indication of reduced flow rate. The only indication will be a channel outlet high temperature alarm.

If boiling of all or many of the fuel channels has occurred due to overall low coolant flow, then the flow monitored channels will produce a reactor trip on low coolant flow.

A second possible cause for the boiling is a falling heat transport system pressure. A low pressure alarm alerts the control room operator so that remedial action may be taken.

Boiling in Fuel Channels Designed for Limited Boiling

Nucleate boiling may be designed to occur in the final section of the fuel channels when at full power. This is normally referred to as bulk boiling. In this situation, conditions will change at the channel outlet header as the reactor power is increased.

Each channel ΔT will increase with power until the saturation temperature for the HT pressure is reached. At this point, the D_2O will start to boil, initially at the channel outlet, and the *temperature will now stay constant*. *As the channel produces further* power, the temperature will not rise but more vapour will be produced progressing towards the channel inlet. If 3% boiling was designed to occur, then the fluid leaving the channel would be a mixture of 3% vapour and 97% liquid by weight.

Therefore, once saturation temperature is reached

(a) the only change with power will be the % of vapour leaving the channel, and

(b) the mass flow rate, as a rule of thumb, will decrease (for the same power) by the % increase in vapour. This decrease is due to the increased flow resistance in the channel due to the larger volumes of vapour.

Q8.20 Briefly explain how the HT fluid temperature and fluid quality change as increasing reactor power produces bulk boiling.

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Loss of Coolant Accident (LOCA)

In this situation, the prime concern is that the reactor should be shutdown safely. This means the provision of cooling for the fuel at all times.

Any loss of coolant which results in the pressurizing system being unable to maintain pressure is defined as a LOCA. If pressure control can be maintained in the HT systems, it is considered a leak.

Small LOCA

In this situation the pressure in the heat transport system will fall gradually until the saturation pressure is reached. At this point, boiling in the channel occurs and the pressure is now determined by the temperature of the liquid which will be relatively stable.

The problem is now that the pressure transient will stabilize and the fuel sheath will become damaged due to the impaired heat transfer resulting from the steam which blankets the bundle. This happens in a very short time; a few minutes from the commencement of bulk boiling.

The solution to this problem is to rapidly reduce the heat production of the reactor by a reactor trip and to initiate a rapid cooldown (known as "crash-cool") to reduce the HT temperature and therefore pressure to a value which will facilitate emergency core cooling.

Major LOCA

In a loss of coolant condition where the break in the Heat Transport System pressure boundary is massive, the drop in both temperature and pressure of the coolant will be very rapid. Consequently, the system will have already been "crash-cooled" by the massive leak and Emergency Coolant Injection may begin.

The Emergency Coolant Injection System (ECIS) is designed to remove the fission product decay heat from the fuel following a LOCA. The reactor power drops from 100% to around 6% before the injection occurs. The 6% full reactor power represents the initial decay heat from the fission products.

The initial inventory of ECI water (light water) is injected into the core by high pressure gas or high pressure pumps depending on the station. A more detailed description of the general operation of ECIS as well as the differences at the various stations can be found in Reactor Boilers and Auxiliaries, Course 233.

In all stations fuel cooling is maintained in the recovery phase by recirculating the water discharged from the break by pumping it from low level sumps.

Indications of a Loss of Coolant

The single most important parameter associated with the detection of a LOCA is by definition, Heat Transport pressure.

Evidence of low HT pressure sustained over several minutes or low HT pressure AND evidence of the presence of high energy fluid within areas surrounding the HT system are used as indication of a likely LOCA and initiating auto actions for ECIS operation.

Q8.21 Explain two conditions which would result in channel boiling.

Q8.22 Explain, in general how a LOCA is detected.

Q8.23 Explain why, in the event of a LOCA, (small or large) it is necessary to establish Emergency Coolant Injection to the core.

Q8.24 How does a massive rupture in the heat transport system affect the rationale explained in Q8.23.

Q8.25 Explain the basic emergency core injection system at your station.

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Heat Transport Thermosyphoning

As fluids are heated they become less dense and equally, as they are cooled, they become heavier. By carefully selecting the elevations of the reactor and the steam generators, a thermosyphon may be established.

The hot D_2O leaves the reactor outlet headers and is physically pushed up to the steam generator where it travels up one side and returns as cooler fluid, down the other side of the tube bundle, back to the reactor via the HT pump (pump is turbining).

Under the correct conditions, the flow as described previously, will occur without the pumps due to the natural convection caused by the temperature differences within the HT system.

Thermosyphoning can only exist when the steam generator is at a lower temperature than the HT circuit and there is no excessive boiling in the HT circuit which would allow vapour to collect at the top of the tubes in the steam generator.

The temperature at the reactor outlet header is used to monitor the thermosyphon. If the HT temperature is rising towards the saturation value, vapour may be produced which may impair the thermosyphon. More heat must be removed from the HT system and this is achieved by lowering the temperature of the steam generator by removing more steam and thereby lowering the pressure. To maintain the viability of thermosyphoning, pressure control must be maintained at a normal setpoint. This will prevent boiling (and possible vapour locking) which would occur on loss of pressure.

Q8.26 Briefly explain how the HT thermosyphon is established and how ROH temperature is used as a datum for the control of the thermosyphon.

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MODULE 8 - ANSWERS

Q8.1

The three sources of heat for the reactor are:

(a) Fission heat from the fuel.

(b) Heat from the decay of fission products.

(c) Heat produced by the operation of the HT pump. This heat is from the HT system.

Under power operating conditions, the heat generated by fission within the fuel is by far, the largest of these heat sources. The heat removed by the flow of the heat transport fluid is exchanged in the steam generator.

In a shutdown condition, the quantities of heat produced are relatively small, (less than 6% of full load power) and are handled by the shutdown cooling system (or maintenance cooling).

Q8.2

Limiting the temperature rise across a non-boiling fuel channel will ensure that fuel bundles are not subjected to conditions beyond their operating limits. Since channel power and mass flow rate determine the temperature rise across the channel, there must be a maximum allowable channel outlet temperature (and therefore temperature rise) which corresponds to the channel power at which high powered bundles approach their maximum operating limits.

For a boiling fuel channel, the channel outlet temperature is not useful for monitoring that channel/bundle power limits are not exceeded because as long as there is liquid present in the channel, the outlet temperature will be the saturation temperature.

Q8.3

For channels where boiling occurs, it is most important to ensure sufficient liquid is present to provide adequate fuel cooling. We do this by monitoring the amount of steam produced by either,

(a) Comparing volumetric flow rates at channel inlet and outlet for fully instrumented channels. The flow rates will be equal for no boiling and the outlet flow rate will exceed the inlet if boiling is occurring. The difference in flow rates is used to calculate the percentage of steam present.

(b) Using flux mapping in conjunction with bulk power measurements. Flux maps are prepared with the aid of computer simulations and measurements of flux at a large number of strategic locations in the core. Bulk thermal power is determined using a combination of boiler steam and feedwater flows and boiler temperature measurements.

Q8.4

From the text, we saw that channel power was determined by the flow rate and the change of enthalpy across the channel, ie,

$$Q = \dot{m} \times \text{Change of Enthalpy}$$

where Q is the channel power, and

$\dot{m}$ is the channel mass flow rate

The channel power remains constant and the channel flow rate decreases. In this event, the change in enthalpy must increase in direct proportion with the falling flow rate.

$$Q = \underset{\downarrow}{\dot{m}} \times \text{Change} \overset{\uparrow}{\text{of}} \text{ Enthalpy}$$

The change in enthalpy is the difference between channel outlet enthalpy and channel inlet enthalpy. However, the channel inlet enthalpy remains essentially constant. Thus, the only way that the change of enthalpy across the channel can rise, is for the channel exit enthalpy to rise.

Q8.5

As explained in the previous question, the temperature of the coolant at the outlet end of the channel will start to rise until it reaches 299°C which is the saturation temperature corresponding to 8.47 MPa(a). Boiling will start at the channel outlet and gradually progress down the channel until thermal equilibrium is reached, with the outlet temperature remaining at the saturation value.

Q8.6

At zero power hot, the steam generator temperature, channel inlet and outlet temperatures, would all be equal at 266°C. The saturation pressure corresponding to 266°C is 5.17 MPa(a). This is the pressure which would exist in the steam generator at this temperature.

Q8.7

As seen in problem Q8.5, the steam generator temperature will be equal to the average heat transport temperature at zero reactor power with the systems fully warmed.

To transfer thermal energy from the HT system to the steam generator, a temperature difference must exist. The only way that this can happen is for the steam generator temperature to fall below the average HT temperature as power increases.

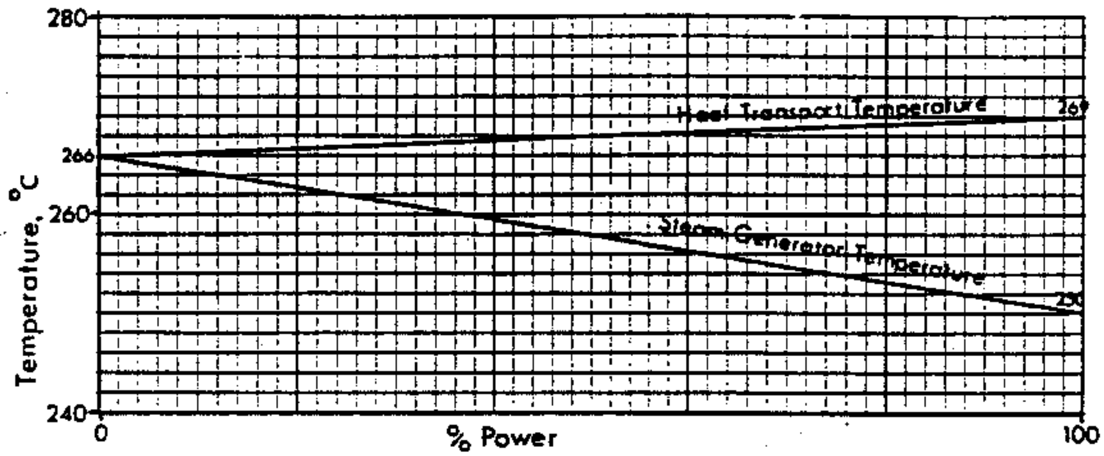


Figure 5
Temperature vs % Full Power

Q8.8

At zero power hot (fully warmed up) when the steam generator and reactor are at operating temperature, the average HT temperature and the steam generator temperature will be equal. If the steam generator pressure is 4.25 MPa(a), then the temperature is 254°C. At this condition, the average HT fluid temperature is also 254°C.

Q8.9

For a system with a pressurizer, the steam generator temperature is going to remain constant between 0% and 100% full power. In order to transfer the heat to the steam generator, there must be a temperature difference between the HT fluid and the steam generator. The average temperature of the heat transport fluid must be higher than that of the steam generator. This is shown in Figure 6 where the average HT temperature leaves the steam temperature at 254°C and rises to a higher value around 277°C.

The value of 277°C cannot be readily determined in this case because of reactor design - eg, inner and outer zones and external preheater.

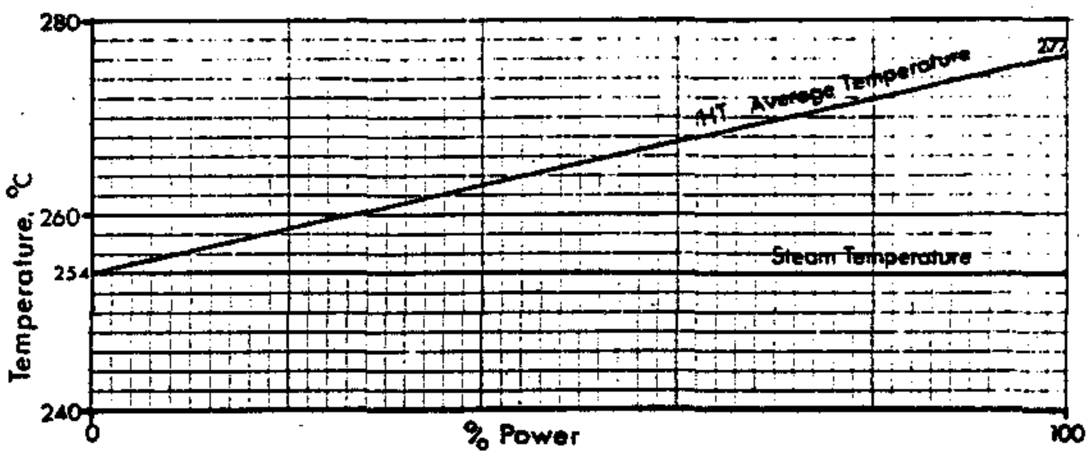


Figure 6
Temperature vs % Full Power

At full power, the channel ΔT will be 53°C in which case the channel outlet temperature will be 26.5°C above the average value and the channel inlet temperature will be 26.5°C below the average value (see Figure 7).

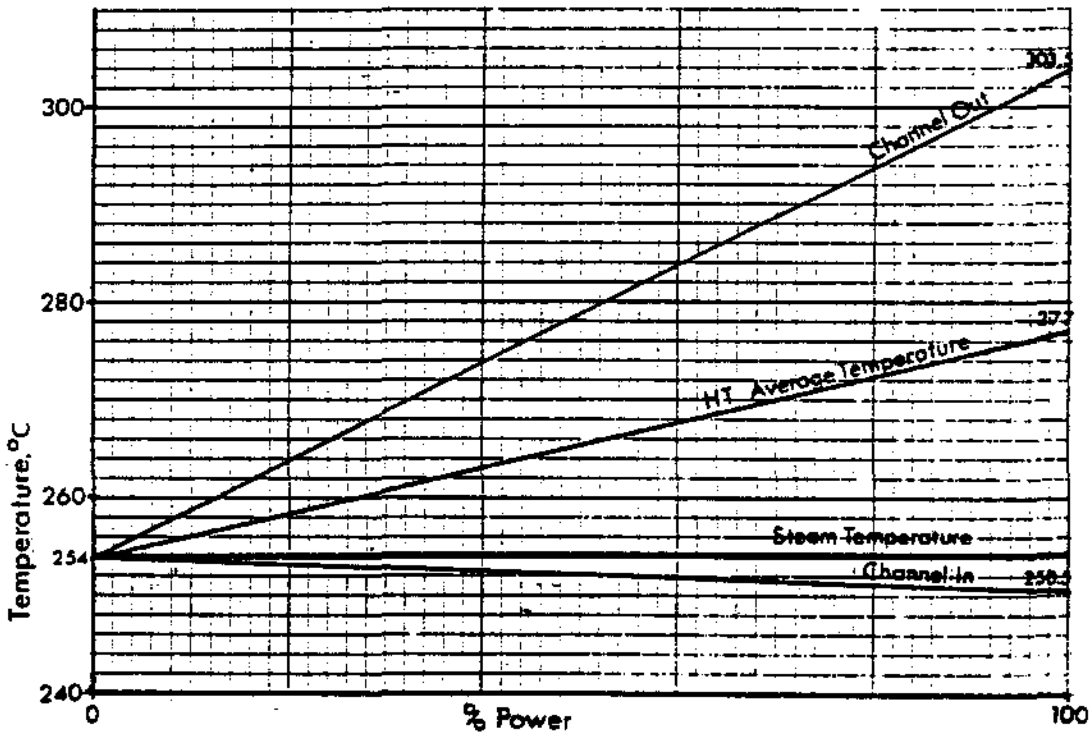


Figure 7
Temperature vs % Full Power

08.10

Feedwater is heated in two stages in the steam generator. Initially, the temperature is raised from around 175°C to 250°C as sensible heat is being added. Secondly, the liquid is turned into vapour as the latent heat of vapourization is added.

The immediate effect of losing feedwater to the steam generator is a reduction of heat transfer capacity, around 17%, due to the sensible heat which is no longer being removed. At this point, a thermal power mismatch occurs and the HT average temperature and pressure starts to rise.

If power is not reduced, boiler level will fall until tubes are uncovered and the heat transfer will be further impaired.

These conditions will both result in a massive thermal power mismatch as a result of having lost the major heat sink.

08.11

(a) Reactor power greater than available heat sink.

(b) Loss or impairment of HT coolant flow.

(c) Pressure control system malfunction allowing an uncontrolled increase in pressure

(d) Loss of feedwater supply causing an immediate loss of heat sink from the preheater section.

08.12

The two major problems of low HT pressure concern the effect vapour production within the D_2O has on the (1) Heat Transport Pumps, and the (2) Fuel in the Channel.

To avoid cavitation in the HT pumps, there is a minimum suction pressure below which pressure should not fall. This value of suction pressure depends upon the temperature of the heat transport D_2O. If cavitation persists over a sufficiently long period of time, pump damage and system damage may result. In addition to this effect, the flow through the pump will be reduced and this could result in an increase in HT temperature due to the reduction of flow through the reactor.

If the HT pressure drops to the saturation pressure corresponding to the HT temperature, vapour will be produced in the fuel channel. If large scale boiling occurs, this will drastically reduce the heat transfer from the fuel to the D_2O. The result will be a rapid increase in fuel and sheath temperatures and the increase may produce fuel sheath failure and fuel damage.

08.13

At PNGS-A, the reactor design was such that the volume of the D_2O in the heat transport system should remain sensibly constant over the whole reactor power range. The average heat transport temperature only changes by 3°C, from 266°C at 0% to 269°C at 100% power. This change in average temperature of 3°C means that the change in fluid volume is less than 1%. Boiling in the fuel channels is not a designed feature at PNGS-A.

At BNGS-A, there are two major differences compared to PNGS-A:

(a) The average HT temperature rises by some 27°C.

(b) Boiling is allowed to occur in some fuel channels.

As a result, there is a significant increase in HT fluid volume as the power is increased from 0% to 100%. The increase in fluid volume amounts to 17 m^3.

For the CANDU 600 the increase in fluid volume is nearly 12 m^3.

Q8.14

As we have already seen, the volumetric expansion of the HT fluid at PNGS-A and B, when at power, is not very large due to the HT average temperature being held about constant.

Control of the heat transport system pressure is effected by feeding D_2O into the HT circuit using the pressurizing pumps and by bleeding D_2O from the circuit at the HT pump suction headers. The shrink and swell of the HT system fluid is accommodated by the D_2O storage tank.

If low pressure exists in the HT circuit, the bleed valves will close and, conversely, if high pressure exists, the bleed valves will open to reduce the system pressure to the programmed value.

At Bruce or Darlington, the change in HT fluid volume with power is much larger than that at PNGS-A and exceeds the rates of change which could be handled easily with a feed and bleed system alone.

The HT system is connected to a pressurizer which is partially full of D_2O liquid. The pressurizer acts as a receiver for the D_2O resulting from the HT swell and also acts as a pressure control device. The vapour space is compressible and acts as a cushion for any pressure fluctuations.

If the HT pressure is high, the steam bleed valves on the pressurizer opens to reduce the system pressure. If the system pressure is falling, electric heaters in the pressurizer raise the pressure in the vapour space and increase the HT pressure. A level control system associated with the pressurizer is used to ensure correct liquid level is maintained over the power range.

Q8.15

(a) Pressurizer System

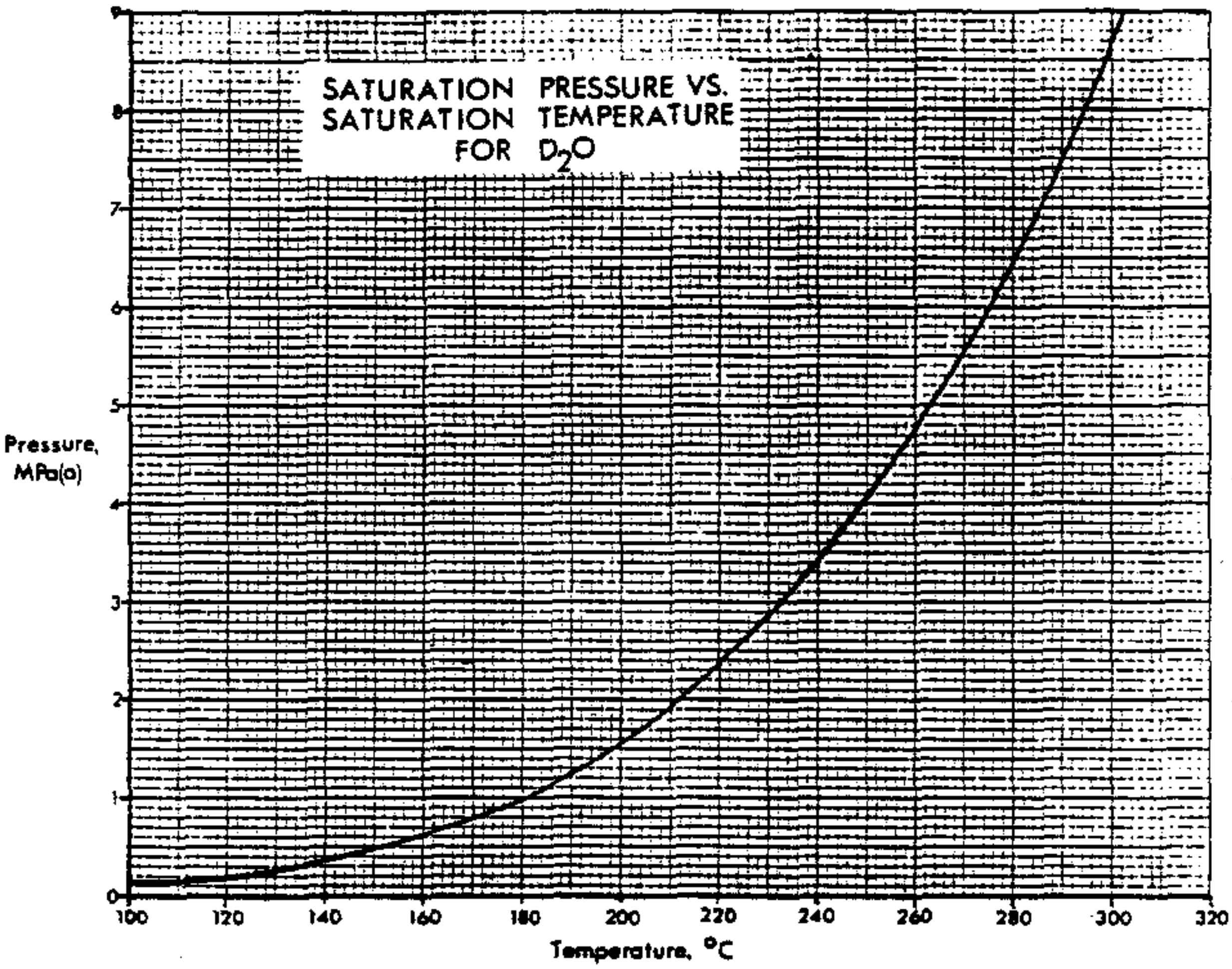
When the reactor power exceeds the available heat sink, the average HT temperature will increase, causing an increase in HT fluid volume. This will cause a sufficient increase in HT pressure to force D_2O into the pressurizer giving an increased level. On a very high level, a reactor setback is initiated to reduce reactor power in an attempt to restore thermal equilibrium.

(b) Feed and Bleed System

For a feed and bleed system, the bleed condenser level will increase due to the increased bleed initiated by the pressure control system. On a very high level, a reactor setback is initiated leading to a reduction in reactor power which may restore thermal equilibrium.

08.16

The heat-transport fluid will shrink at a greater rate than can be matched by the HT pressure control system and the temperature and pressure will fall. As soon as the pressure reaches the saturation value, the HT system will start to boil (boiling in the fuel channels.)

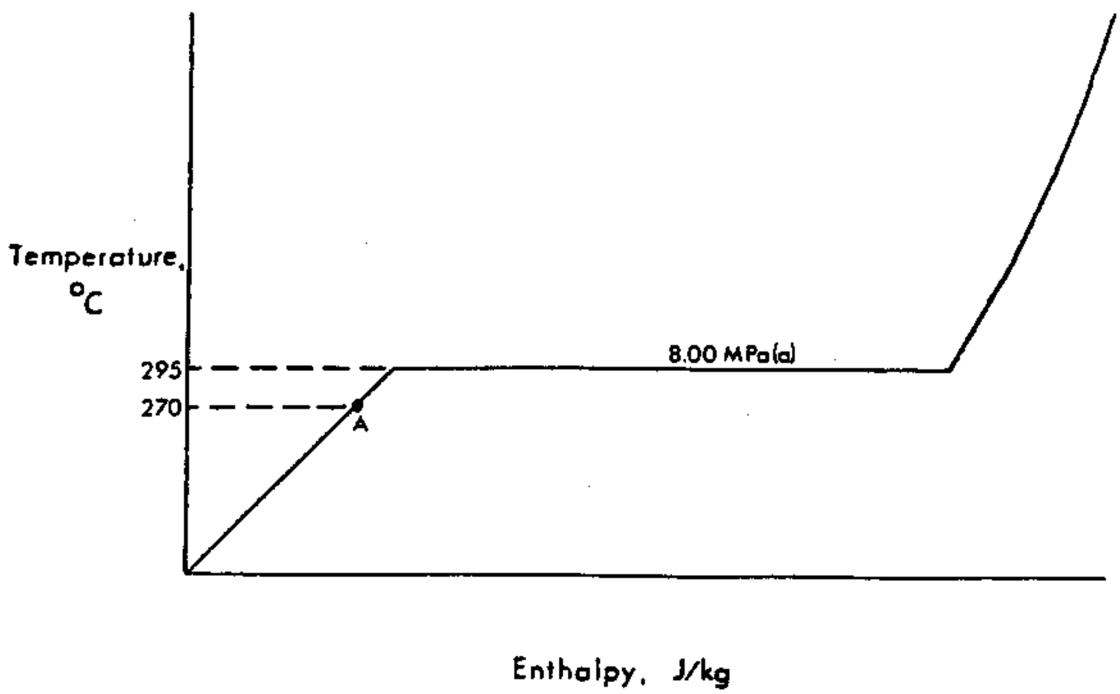


Saturation Pressure vs Saturation Temperature for D_2O
Figure 8

The graph of saturation pressure/temperature (see Figure 8) is useful to compare actual PHT pressure with the saturation pressure corresponding to the HT temperature. The actual HT pressure should always be higher than the saturation pressure.

If significant boiling does occur, heat will not be removed as effectively from the fuel and fuel temperature will rise. This in turn could lead to an increased risk of fuel failure and release of fission products into the coolant; a very undesirable outcome.

08.17

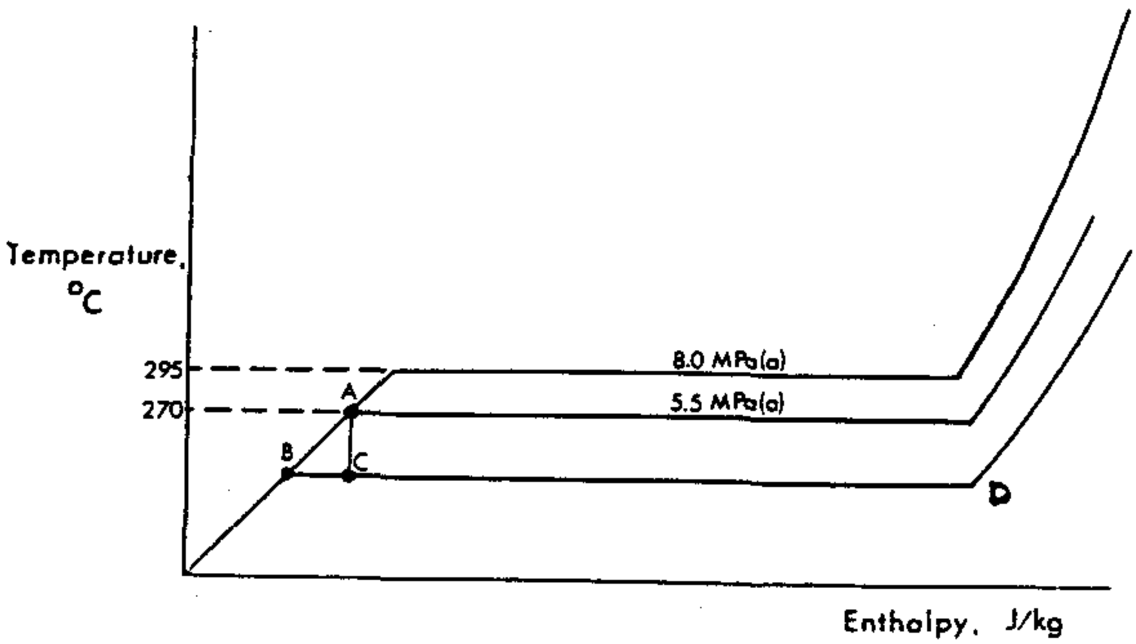


Temperature vs Enthalpy
Figure 9

At 8.1 MPa(g) (approximately) from steam tables, the saturation temperature is 295°C (see Figure 9). The actual temperature of the HT liquid is 270°C (Point A) which means that it is subcooled by 25°C.

08.18

When the pressure has fallen to 5.5 MPa(a), the corresponding saturation temperature is 270°C (see Figure 10, Point A). This is the actual temperature of the liquid. Any further reduction in pressure will result in bulk boiling as the enthalpy, which is in excess of that needed for saturated liquid, supplies the latent heat of vapourization for vapour production.



Temperature vs Enthalpy
Figure 10

The enthalpy of the fluid does not change. At point A, there is saturated liquid at a pressure of 5.5 MPa(g). If the pressure was to fall to a lower value, there would be a two-phase fluid. These two phases would be:

(a) Saturated liquid at point B.

(b) Vapour generated with specific enthalpy D. You can see that for saturated liquid, the specific enthalpy at B is less than that at A, as a consequence the fraction of vapour by mass is given by (B-C)/(B-D).

Q8.19

The main concern with excessive channel boiling is dry out and the loss of heat transfer that occurs due to the poor heat transfer through the D_2O vapour compared with the heat transfer to the liquid.

Although zircaloy 4 has a melting point of around 1800°C, sheath failure is likely to occur between 800° to 1100°C.

Failure of the fuel sheath and the release of fission products into the HT system are major considerations that depend upon maintaining the integrity of the fuel sheath.

The fuel temperature at the centre of the pencil is around 2300°C and the melting point is around 2800°C. A loss of cooling, occurring when the channel is boiling, could result in fuel melting if no action is taken.

Q8.20

When the liquid coolant has reached the saturation temperature and vapour is about to be produced, the indicated temperature rise will stop. From this point on, we have little idea of what is actually happening in the channel with respect to boiling.

As power is increased, more vapour is produced at a constant temperature and therefore, the channel ΔT is no longer an indication of channel power.

Q8.21

The two basic conditions which will result in channel boiling are:

(a) A sufficient reduction of coolant flow.

(b) A significant reduction in heat transport system pressure.

As the coolant flow is reduced, the temperature has to rise in proportion to the loss of flow so that the same quantity of heat is removed. As soon as the temperature of the coolant reaches the saturation temperature, vapour generation begins. Once vapour production starts, the indicated coolant temperature remains constant.

If the pressure falls to the saturation pressure corresponding to the temperature of the HT coolant, vapour production will again begin. The production of large volumes of vapour has the effect of reducing or even arresting the rate of pressure reduction. This is a dangerous condition because once this has happened, the channel voiding is established and fuel failures may go undetected.

08.22

(a) Low HT pressure for a prolonged period.

or

(b) Low HT pressure and evidence characteristic of hot HT coolant in areas surrounding the heat transport system.

08.23

If the loss of coolant is large enough that the HT system pressure starts to fall, then channel boiling will occur at the saturation pressure. When this happens, the rate of pressure decrease will reduce and the rate may even be zero if sufficient vapour is produced to match the leak rate.

At this point, vapour will fill the channel, boiling will occur and heat transfer from the fuel will be dramatically reduced.

The key and immediate objective is to re-establish fuel cooling as soon as possible which means that liquid must rewet the fuel bundles.

To achieve this, the reactor is crash cooled using the steam reject or boiler safety valves, depending on the station. This action significantly reduces HT system pressure and temperature in a few minutes.

As soon as HT pressure falls low enough, emergency coolant injection can commence. This provides another source of coolant if there is not enough HT D_2O left in the circuit to maintain cooling.

08.24

The basic difference between a small LOCA and a major LOCA is the time taken for the system pressure to fall. In a small LOCA with crash cooling, the time scale is in the order of minutes. With a major LOCA, the crash cooling and loss of pressure have virtually occurred simultaneously. As a result, emergency core injection can begin immediately. This reduces the time between the loss of pressure when boiling of the coolant occurred and the point when emergency core injection commenced. Whether the injection will keep the fuel cool enough to prevent sheath failure is an extremely complex problem depending on the physical position of the rupture, size of the system break, operating condition of the reactor prior to the loss of coolant, etc. It is difficult to state with any accuracy, the degree of success that will result in a given set of circumstances.

What we can say is that whatever else may occur in any postulated reactor condition, the fuel should not become unsafe due to loss of coolant.

08.26

The primary heat sink, which is the steam generator, is physically higher than the reactor. The less dense D_2O will rise up to the steam generator whilst the D_2O that is cooled in the steam generator, will become more dense and fall to the suction of the HT pump, thus establishing coolant flow around the system.

The reactor outlet header temperature is monitored to ensure that it does not reach the saturation value when vapour would be produced. This temperature is also used to ensure that sufficient temperature difference exists between the steam generator and the reactor. This condition can be ensured by lowering the steam generator pressure and hence the temperature.