125

HEAT & THERMODYNAMICS

MODULE B.1

REACTOR

Heat & Thermodynamics

MODULE B.1

REACTOR

Course Objectives

The student will be able to:

1. Briefly explain how reactor channel blockage can be detected and may be confirmed.
2. Briefly explain one major problem resulting from channel blockage.
3. Briefly explain why crash cooling is necessary for a leak which results in a very low rate of pressure decrease in the heat transport system.
4. Briefly explain how a loss of heat transport coolant may be detected.
5. Briefly explain how a small loss of coolant may eventually produce fuel failure similar to that expected in a major LOCA.
6. Briefly explain the immediate and longer term effects of losing feedwater supply to the steam generators.
7. Briefly explain how the temperature and quality of the PHT coolant change when bulk boiling occurs.
8. Explain how the PHT thermosyphon is established and how the ROH temperature is used as a datum for the control of the thermosyphon.

Enabling Objectives

The student will be able to:

1. Briefly explain four possible reasons for a high heat transport system pressure.

2. Briefly describe two major problems that could result from a low heat transport system pressure.

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 dependant systems, eg, the moderator system, the heat transport system and the steam system. It is virtually impossible to discuss one system without referring to another.

As a heat source, the reactor system has three inputs:

a) Decay heat from fission products.
b) H.T. pump heat.
c) Fission heat.

When at power the fission heat is, by far, the largest of these three terms. At low power, the pump heat becomes significant.

The only ways that the heat produced within the reactor can be removed are by the heat transport system and to a much lesser degree, by the moderator system.

The main purpose of the heat transport system is to remove the heat from the three sources that we have already mentioned, ie, decay and fission heat in the fuel bundles and the pump heat. At power, this is done with a constant mass flow of D_2O.

The main method of removing heat from the heat transport system is via the steam generators. In the event that the steam generators are not available to act as a heat sink for the heat transport system, the reactor is tripped because there is no backup capable of removing the full load 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 produced by the decay of fission products. The heat from the decay of fission products is less than 6% FLP.

B.1.1

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

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

Going right back to design considerations for the ideal fuel for the reactor, three of the criteria which we would like to satisfy are:

a) The fuel should have a good thermal conductivity.
b) The fuel should not react chemically with the heat transport fluid.
c) The fuel should be dimensionally stable over its life cycle.

The choice that is to be made is between a metallic fuel and a ceramic fuel. If a metallic fuel is used, it reacts readily with hot D_2O in the event of a leak in the fuel sheathing. In addition to this problem, metallic fuel may experience severe mechanical distortion which results in premature sheathing failure.

If a ceramic fuel is used, we have very good dimensional stability but the heat transfer coefficient is significantly reduced in relative terms because a ceramic is a thermal insulator. A ceramic does have one benefit, however. It has a high melting point and the melting point of uranium dioxide is 2800°C.

The temperature profile of a fuel element may be seen from the diagram.

Calculate the total reactor power. Check the notes at the end of the module.

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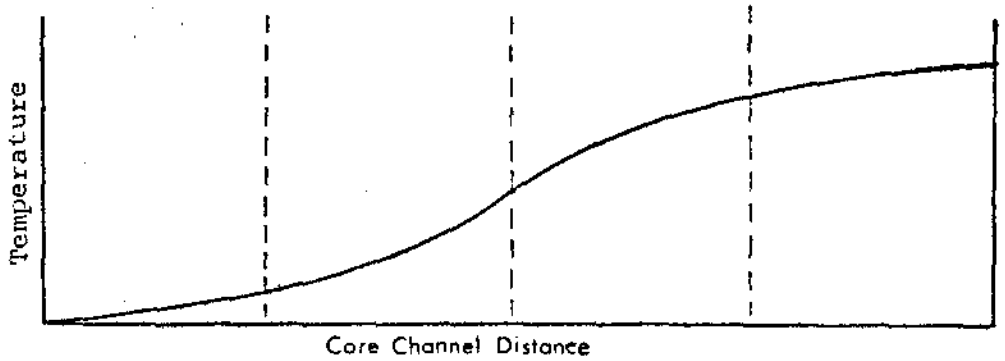
We calculated the total channel power using the mass flowrate and the temperature rise across the channel. In principle, this was relatively easy to accomplish.

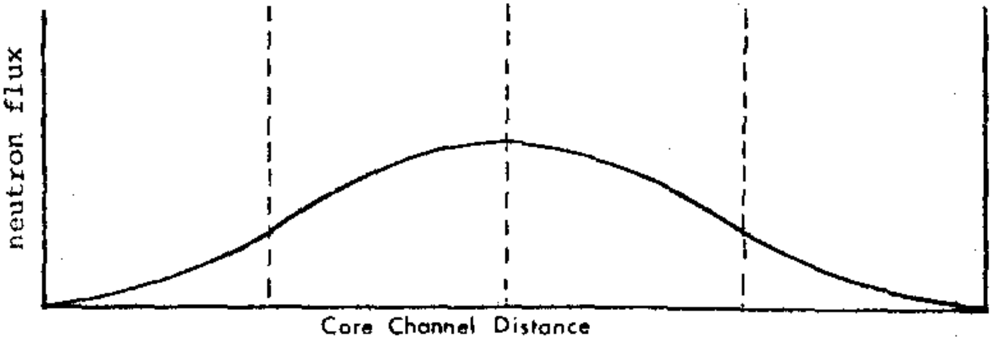
We know that the fuel element sheath has a temperature limit and that the rationale upon which this limit is based is the avoidance of excessive fuel temperatures leading to fuel sheath failure.

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.

We have to look backwards from the channel coolant temperatures to the basics of fuel channel physics to find out about the individual bundle powers.

The neutron flux distribution along a fuel channel is a familiar shape. It represents the amount of power being produced at that point in the channel and we can see that at the outer sections of the channel, the neutron flux or power levels are lower than in the centre of the channel.





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

The basic shape of the flux distribution remains fairly constant although some changes will occur in shape due to positions of control and reactivity mechanisms; direction of fuelling and position of the channel in the core.

In practice, the power distribution along the channel is also affected by the fuel burnup. The effect of the fuel burnup is to produce a power distribution curve which is not the same shape as the flux curve. The major effect of fuel burnup is ignored in this discussion.

By mathematically calculating the area under the flux distribution curve, the channel power may be determined and the power being produced by the fuel bundles in the highest flux region in the centre of the channel may also be determined.

We know the nominal operating bundle power limit; at PNGS-A, it is 636 kW and at BNGS-A, it is 827 kW. The maximum or licensed power limit is 705 kW/bundle at PNGS-A. If any single bundle in the reactor exceeds this value, we have a problem. The reactor is designed so that the operating bundle powers normally remain below this quoted value. However, due to the effects of reactivity mechanisms and fuel burnup on the power distribution, fuel bundles may approach the licensed power limit. In this case, the reactor must be derated to prevent the licensed power limit being exceeded.

In summary, using the flux shape and the maximum values for bundle power, a particular channel is designed to produce a maximum amount of power. Knowing the maximum amount of power and the mass flowrate of the coolant, we could find the temperature rise across the channel that represents this amount of power.

If this temperature rise is exceeded, it would suggest that the channel may be producing more power and in this event, the fuel bundles in centre channel would be operating outside design limits.

The increase in fuel channel temperature rise may not be due to an increase in power.

When we calculated the channel power earlier in the module, we used an equation:

Power = Mass Flowrate x Change in Enthalpy.

Let's expand this a little further:

Power = Mass Flowrate x (Enthalpy Out - Enthalpy In).

Keep the channel inlet temperature constant. Keep the channel power constant. The channel mass flowrate now reduces due to channel blockage.

Going back to the power equation, let's identify those quantities which are constant and see what this produces.

$$\textbf{Power} = \textit{Mass}\ \underset{\downarrow}{\textit{Flowrate}} \times (\overset{\uparrow}{\textit{Enthalpy}}\ \textit{Out} - \textbf{Enthalpy In}).$$

The Power will remain constant.
The Enthalpy of the coolant into the channel will remain constant.
The change that we now make is to reduce the coolant flow in the channel.

If the channel power remains constant, the only way that this can occur is for the reduced coolant flow to pick up the same amount of heat. In doing so, the enthalpy of the coolant out of the channel becomes greater, ie, the temperature rise across the fuel channel increases.

B.1.4

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 and explain what indications would suggest a blocked fuel channel.

B.1.5

A fuel channel is operating normally with the following conditions:

Channel outlet temperature 296°C.

Channel outlet pressure 8.47 MPa(a).

$(t_s) = 299°C$.

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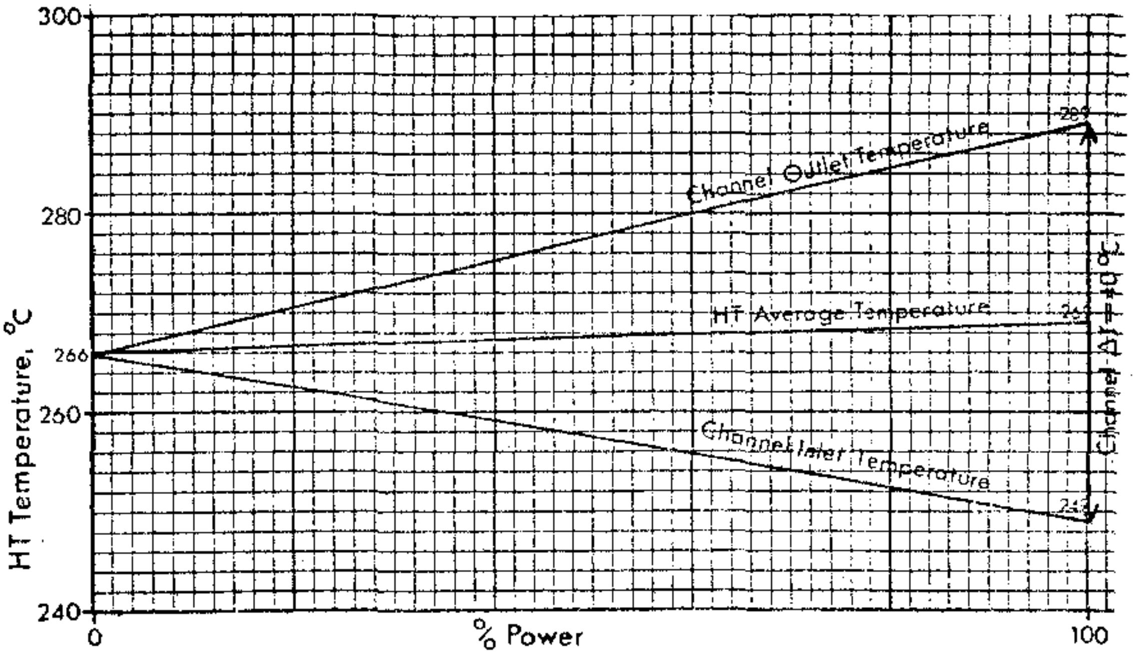
As we have already seen, the channel power with constant mass flowrate, is proportional to the channel ΔT, provided no boiling occurs in the channel.

If the outlet and inlet temperatures are equal, then there is no temperature difference and reactor power is essentially zero. As the power is increased, the channel ΔT increases to a maximum at full power.

At PNGS-A, the channel ΔT at full power is 40°C. At BNGS-A, the maximum ΔT occurs in the inner zone and is 53°C at full power.

There are some significant differences in the method used to obtain the ΔT across the fuel channel at PNGS-A and at BNGS-A.

At PNGS-A, the average primary heat transport temperature is kept sensibly constant, rising from an average value of 266°C at 0% power to an average value of 269°C at 100% power.



From the diagram, we can see that the channel inlet temperature falls as the channel outlet temperature rises and the average temperature stays sensibly constant.

B.1.6

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 PNGS-A example shown above?

B.1.7

In order to transfer heat from the heat transport system to 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 - 100% at PNGS-A?

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

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At BNGS-A, the situation between the heat transport system and the steam generator is reversed. The pressure in the steam generator is kept constant at 4.25 MPa(a) from 0 - 100% power.

B.1.8

From the information in the previous paragraph relating to BNGS-A, what is the heat transport average temperature when the unit is at zero power hot.

B.1.9

How would you expect the heat transport average temperature (inner zone) to change with power for the BNGS-A illustration. 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 for inner zone.

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 PHT circuit. The 'solid' system has very little vapour space and the PHT system pressure is very sensitive to changes in fluid volume. This design uses a bleed cooler for controlling the pressure of the PHT system. condenser

The second design uses a pressurizer which contains a large volume of D_2O vapour that expands when the liquid volume in the PHT decreases and is compressed when liquid volume increases. This arrangement is very much less sensitive to the changes in PHT 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, is immediate. In the pressurizer system the rate of change is very much smaller.

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

At PNGS-A, this final high pressure trip occurs at 9.55 MPa(a) and at BNGS-A, the pressure is 9.66 MPa(a).

The heat transport high pressure may be caused by:

a) A loss of reactor power regulation as a result of which the nuclear power now exceeds the heat sink capabilities.

b) A loss of circulation of the heat transport fluid resulting in a loss of heat transport capacity.

c) A loss of heat transport pressure control.

d) A loss of feedwater to the steam generator rapidly reduces the rate at which heat is removed from the H.T. system.

e) Total unavailability of steam generator as a heat sink.

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

As the steam generator tubes become uncovered, the steaming rate decreases because of reduced heat transfer surface area. This situation further accelerates the rise in the PHT system temperature.

In this situation, the primary heat sink for the reactor is lost and the reactor must be shut down quickly and placed on shutdown cooling if massive channel voiding is to be prevented.

This situation represents a large mismatch in thermal power. The PHT pressure will rise rapidly up to the saturation pressure and then more slowly as vapour is produced.

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B.1.10

Explain the immediate and longer term effects of losing feedwater to the steam generators.

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A low pressure in the heat transport system may be caused by one of two conditions:

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

b) A loss of coolant from the PHT circuit.

In both cases, the rate of volume reduction may be greater than the make-up from the pressurizing circuit and the PHT system pressure will fall as a result.

A low pressure in the heat transport system may produce the following problems:

a) There is a minimum value of pressure for the heat transport pump suctions to avoid cavitation. If this pressure is reached, a reduction in coolant flow and pump damage will result.

b) As the pressure falls, the heat transport fluid has more heat than is needed 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 will occur due to the rapid rise in fuel temperature.

B.1.11

State the heat transport pressure which produces a reactor trip at your station.

B.1.12

Explain four significant causes that produce a high heat transport system pressure and two major problems that could result from a low heat transport system pressure.

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 heat transport system. Needless to say, the systems at each station are different!

PNGS-A

At PNGS-A, the major benefit of having the heat transport average temperature sensibly constant is that there are no great changes in heat transport 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 heat transport pressure. Pressurizing pumps return the feed to the heat transport system, thus tending to raise the pressure. The shrink and swell effects of the heat transport system are accommodated by the D_2O storage tank, which also provides the suction for the heat transport 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. The first valve opens at 9.1 MPa(a) and the rest at 9.55 MPa(a).

In the event of a problem with the bleed condenser that results in high pressure, a relief valve is installed which operates at 8.7 MPa(a) and causes heat transport D_2O to be discharged to the boiler room.

BNGS-A

At BNGS-A, there is a considerable rise in the average heat transport temperature for the whole reactor, from 254°C to around 281°C. This temperature rise will result in an increase of heat transport D_2O volume of approximately 5%. This increase in volume amounts to approximately 17 m^3.

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

The pressure control is affected by a pressurizer which acts as a cushion on the heat transport system and absorbs pressure transients. It is similar to a conventional steam drum, having a steam space and a liquid level.

The pressurizer has sufficient capacity to keep the heat transport pressure within the predetermined limits for any normal reactor power manoeuvring.

The heat transport system pressure is determined by the vapour pressure that exists in the pressurizer. If the heat transport pressure rises, steam bleed valves open on the pressurizer to relieve the vapour pressure and thereby reduce the heat transport pressure. The steam from the pressurizer is fed into the bleed condenser.

In the event of a low heat transport 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 heat transport system.

In the event of a high heat transport pressure, the liquid relief valves will open and discharge into the bleed condenser. The relief pressure is 9.55 MPa(a). The reactor high pressure trip is set at 9.66 MPa(a).

B.1.13

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

B.1.14

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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A loss of pressure control of the heat transport system is undesirable for obvious reasons. One of the possible indications of high pressure is a rising level in the pressurizer at Bruce and the Bleed condenser at Pickering. This may be due to a reduction of steam flow from the steam generator which causes the PHT temperature to rise.

For whatever reasons, the heat transport fluid is expanding at a greater rate than the control system can handle. The solution to the problem is to reduce the average heat transport temperature so that the volume reduces. The control action on high level in the pressurizer or bleed condenser is a reactor setback. The reactor setback reduces thermal power and restores the match between the thermal power produced by the reactor and the thermal power removed from the steam generator. As the reactor power is reduced, the PHT temperature falls and the volume of the PHT system is reduced.

This problem is compounded at PNGS-A by the fact that the vapour space in bleed condenser is relatively small and will quickly be used up when the heat transport fluid expands. If the bleed condenser goes "solid", the pressure will rise rapidly. This creates a real risk of rupturing the bleed condenser and creating a major LOCA. This event is avoided by the use of pressure relief valves on the condenser.

B.1.15

Explain the significance of a high level in the pressurizer at BNGS-A or the Bleed condenser at PNGS-A and explain the result of the high level from the reactor control program.

B.1.16

A high level in the pressurizer at BNGS-A and a high level in the bleed condenser at PNGS-A is moving towards the setback value. Is there any action that the operator could take to try to control this condition before a programmed reactor setback or a high H.T. pressure trip occurs? Briefly discuss the major effect of any action you suggest.

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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 heat transport system.

Low pressures in the heat transport system are indicative of three possible situations:

a) Large mismatch in thermal power between the reactor and the steam generator, eg, the inadvertent opening of a large steam reject/discharge valve.

b) A faulty control system which reduces the ability to control heat transport system pressure.

c) LOCA

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

How would the condition be shown on a temperature/enthalpy diagram.

B.1.17

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

B.1.18

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

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The effect of producing a large quantity vapour in the heat transport system such as occurs in a LOCA, produces several problems.

There is a significant rise in the volume of the heat transport fluid due to the much larger vapour volume produced from the relatively low liquid volume.

The vapour, being much less dense, does not absorb as many neutrons as the liquid and this produces the effect of increasing reactivity.

The most serious effect is on the heat transfer mechanism that exists at the fuel bundle. In the channel, the voiding or production of vapour starts where the temperature of the fluid is highest and the pressure is lowest. In principle, the lowest pressure occurs in the centre of the channel because that is where the flow is highest.

The highest temperatures exist at the fuel bundle sheathing as far as the heat transport fluid is concerned. The normal method of heat removal is by forced convection where the liquid swirls past the bundles and becomes heated.

Nucleate boiling increases heat transfer but in nucleate boiling, the liquid remains in contact with the fuel.

The effect of voiding prevents the liquid coming into contact with the fuel bundle due to the vapour being produced.

The only mechanism by which heat can be transferred at this state is by conduction through the vapour. Unfortunately, the thermal conductivity of vapour is extremely low.

The effect of this reduced heat transfer causes the temperature of the fuel elements to rise so that heat is now being transferred by conduction initially and thermal radiation through the vapour as the fuel sheath temperatures become higher.

The major problem is that in this situation, the fuel sheath temperature starts to rise from around 350 - 400°C towards the fuel temperature of around 2300°C. Zircalloy 4 has a melting point of around 1800°C which means that the fuel is quite capable of melting the sheathing.

Long before the melting point is reached, sheath failure will occur; probably in the range 800 - 1100°C, and release of fission products into the heat transport circuit will result.

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.

B.1.19

Explain why uncontrolled coolant voiding is undesirable in the reactor.

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Voiding of the fuel channel may also 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 flowrate. The only indication will be a channel outlet high temperature alarm.

If voiding of all 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 voiding effect is a falling heat transport system pressure. A low pressure alarm alerts the control room operator so that remedial action may be taken.

The values of low pressure alarm are:

PNGS-A 8.5 MPa(a)
BNGS-A 8.92 MPa(a)

Bulk Boiling

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

The channel ΔT will increase with power until the saturation temperature for the PHT pressure is reached. At this point, the D_2O will start to boil, initially at the outlet header, and the temperature will now stay constant at the channel outlet. As the channel produces further power, the temperature will not rise but more vapour will be produced progressing towards the channel inlet as the power is further increased. If 10% boiling was designed to occur, then the fluid leaving the channel would be a mixture of 10% vapour and 90% liquid by weight.

This ratio would be very different by volume, 63% vapour and 37% liquid. Once the temperature reaches the saturation value, the only change with power will be the % of vapour leaving the channel.

In this condition of bulk boiling, it is almost impossible to tell what the vapour fraction actually is and deciding whether a channel blockage exists is a whole new ball game.

One change in flow conditions that will occur with bulk boiling is the mass flowrate, as a rule-of-thumb this will decrease, for the same power, by the % increase in vapour, ie, 20% vapour → 80% original flowrate. This decrease is due to the increased enthalpy of the vapour liquid mixture.

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B.1.20

Briefly explain how the PHT temperature and coolant quality change as increasing reactor power produces bulk boiling.

Loss of Coolant Accident (LOCA)

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

We could define a LOCA as a condition where the loss of coolant was at such a rate that the ability to maintain heat transport system pressure was lost.

At either end of the scale, the two extremes are:

A Massive rupture of heat transport circuit where the pressure is lost almost immediately, and

A Smaller loss rate where the heat transport system pressure is falling gradually.

Small LOCA

In this situation the pressurizing system should be able to maintain pressure in the PHT. If the pressurizing system is unable to maintain pressure, the pressure in the heat transport system will fall gradually until the saturation pressure is reached. At this point, bulk boiling in the channel occurs and rate of pressure decrease is reduced or even halted.

The problem is now that the pressure transient will stabilize and the fuel sheath will become damaged due to the loss of 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 remove the heat from the reactor at a greater rate. This can be done in a "crash-cool" exercise by opening up the steam reject/discharge valves. This has the effect of cooling the heat transport fluid rapidly and minimizing the vapour formation.

The pressure and temperature in the heat transport system will fall rapidly to the lower pressure at which Emergency Injection can begin.

Major LOCA

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

Emergency Core Injection System

The emergency core injection system 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.

At PNGS-A, the injection into the reactor core uses the moderator system and so injection can only occur when the heat transport system pressure has fallen below the moderator pump discharge pressure.

At BNGS-A, light water is used on a gravity feed circuit from a dousing tank housed in the top of the vacuum building. In this case, the heat transport pressure must fall below the static head of the dousing tank before injection can take place.

In both stations, the injected fluid discharges via the rupture to the vaults and boiler room sumps or the fuelling machine duct and is recovered and pumped back into the reactor. Obviously at BNGS-A, there is no highly tritiated moderator D_2O contaminating the station which is an advantage.

Indications of Loss of Coolant

At both PNGS-A and BNGS-A, the heat transport D_2O storage tank accommodates the changing volume of the heat transport fluid. A low level alarm alerts the operator to the fact that there may be a problem, even if the problem is merely due to not having changed the level set point when power manoeuvring.

A loss of heat transport system pressure may be a first indication of loss of coolant.

If the D_2O is leaking into the boiler room, a boiler room high pressure trip may result. Beetle alarms would confirm this leakage. (Note a steam leak would produce similar results.)

If the loss of coolant resulted in voiding in the fuel channel due to low pressure, then the resultant positive reactivity may produce Hi Linear Rate Trip, Hi Log Rate Trip, Hi Power Trip on the reactor.

B.1.21

Explain two conditions which would result in channel voiding.

B.1.22

Explain how a loss of heat transport coolant may be detected.

B.1.23

Explain the effect of a Loss of Coolant on the heat transport system that is large enough to cause a loss of heat transport pressure. Describe the basic steps leading to emergency core injection.

B.1.24

How does a massive rupture in the heat transport system affect the rationale explained in B.1.21?

B.1.25

Explain the basic emergency core injection system at PNGS-A and BNGS-A.

Heat Transport Thermosyphon

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, the thermosyphon may be established.

The hot D_2O leaves the outlet headers and is physically pumped up to the steam generator where it travels up one side and returns as cooler fluid, down the other side of the tube nest, back to the reactor via the PHT pump.

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 D_2O.

The thermosyphon can only exist all the time that the steam generator is at a lower temperature than the PHT circuit and that there is no vapour or gas in the PHT circuit which would collect at the top of the tubes in the steam generator.

The temperature at reactor outlet is used to control the thermosyphon. If the PHT temperature is rising towards the saturation value, vapour may be produced which would prevent the thermosyphon continuing. More heat must be removed from the PHT system and this is achieved by lowering the temperature of the steam generator by removing more steam and thereby lowering the pressure. It maybe possible to raise the PHT system pressure to a value above the saturation value.

If non-condensible gases collect in the steam generator tubes, the thermosyphon will stop and reactor cooling will be lost and the reactor temperature will start to rise and other heat sinks must be used.

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B.1.26

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

You have almost finished this program. Look at the objectives and if you feel you are ready for the criterion test, obtain the test from the Course/Shift Manager.

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When you have completed the test, compare your answers with the self evaluation sheet.

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After you have been signed off by the Course Manager, please take time to complete the course evaluation form and let us know what we can do to make this course more suited to your needs, in format and content.

Answers

MODULE B.1

REACTOR

B.1.1

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 H.T. pump.

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.

B.1.2

As explained in the notes, the heat output from the fuel channel may be expressed as $\overset{o}{Q} = hA\Delta T$

where $\overset{o}{Q}$ is the rate of heat transferred.
h is the heat transfer coefficient which does not alter significantly.
A is the area for heat transfer which is fixed.

The only variable on the right-hand side of the equation is ΔT which is the temperature difference between the hot surface and the coolant.

Thus, if $\overset{o}{Q}$ doubles, then ΔT must double.

We can see this on raising a reactor from 50% power to 100% power. If at 50% power, the channel ΔT is 20°C, doubling the reactor power to 100% will raise the channel ΔT to 40°C, provided no bulk boiling occurs.

For most changes in power, the temperature difference varies directly as the power.

B.1.3

The change in enthalpy across the channel is

$$h_{f_{300}} - h_{f_{250}}$$

$$= 1297 - 1051$$

$$= \underline{246}\ \text{kJ/kg}$$

The channel mass flowrate is 24 kg/s.

Channel Power = Mass Flowrate x Change in Enthalpy

kJ/s = kW = kg/s x kJ/kg

$$= 24 \times 246$$

$$= \underline{5904}\ \text{kW (thermal)}$$

Total power from 420 channels

$$= 420 \times 5904$$

$$= 2479680\ \text{kW}_{th}$$

Total reactor power = $\underline{2480}\ \text{MW}_{th}$

This compares with total reactor power at PNGS-A of 1665 MW_{th} and at Bruce of 2392 MW_{th}.

B.1.4

From the text, we saw that channel power was determined by the flowrate and the change of enthalpy across the channel, ie, $\overset{o}{Q} = \overset{o}{m}$ x Change of Enthalpy

where $\overset{o}{Q}$ is the channel power, and

$\overset{o}{m}$ is the channel mass flowrate

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

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

The change in enthalpy is the difference between channel outlet enthalpy and channel inlet enthalpy. However, the channel inlet enthalpy remains constant. Thus, the only way that the change of enthalpy across the channel can rise, is for the channel exit enthalpy to rise. In other words, the only variables were the flowrate which was decreasing, and the exit enthalpy which had to increase in direct proportion to maintain constant channel power.

One of the first indications of channel blockage would be a rise in the channel outlet temperature. This assumes that no channel voiding is going to occur.

It may be possible to monitor the pressure at either end of the fuel channel using the fuelling machines. The pressure drop is due to that of the fuel plus blockage. This may be compared with similar channels or previous readings.

B.1.5

As explained in the previous question, the temperature will start to rise until it reaches 299°C which is the saturation temperature corresponding to 8.47 MPa(a). At this point, a change of state occurs and the liquid is being turned into vapour within the channel and voiding of the channel is taking place but the temperature will not rise above 299°C.

Suppose the channel had been operating with a designed 10% boiling - how would you know if there was a channel blockage?!

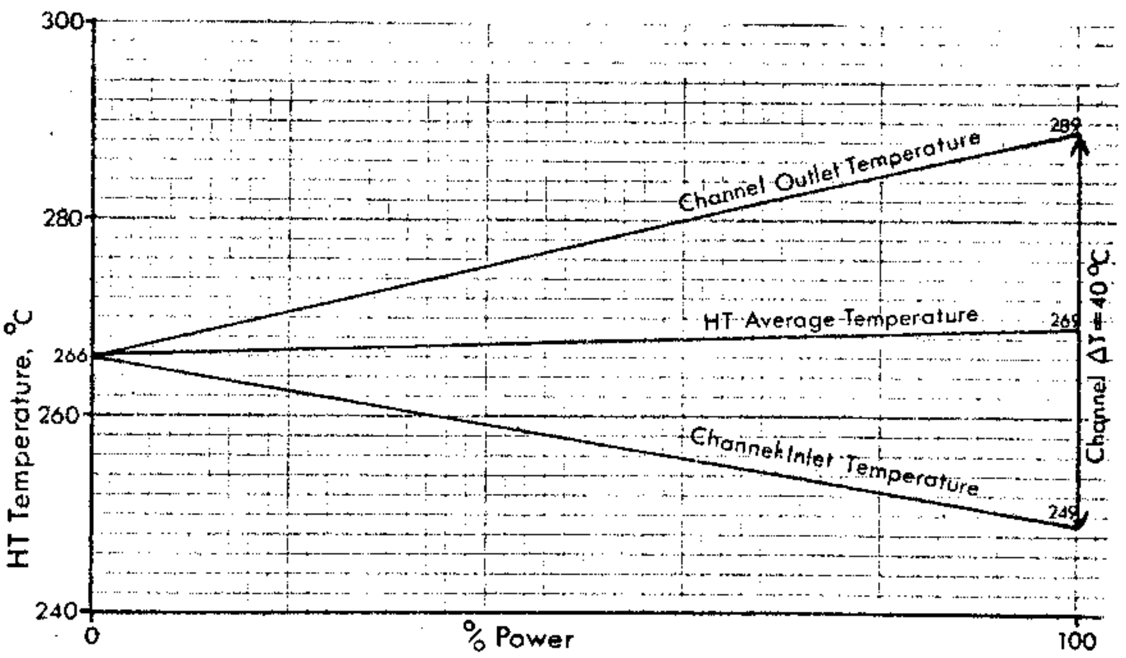
B.1.6

At zero power, 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.

B.1.7

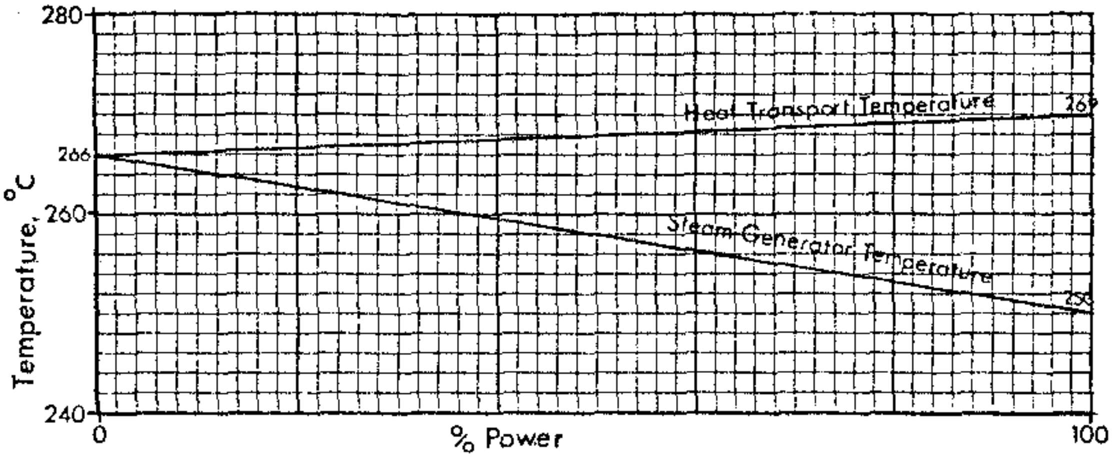
In this case, the heat transport average temperature is almost constant. At zero power but at operating conditions, the steam generator temperature will be equal to the average heat transport temperature.

To transfer thermal energy to the steam generator, a temperature difference must exist. The only way that this can happen is for the steam generator temperature to fall with increasing power. It cannot rise because the reactor is the heat source, not the steam generator. The temperature in the steam generator will always be less than the average heat transport temperature when at power.



The thermal reactor power is around 1665 MW at PNGS-A and this energy is transferred in the steam generator with a maximum temperature difference between boiler inlet and boiler outlet of 40°C - same as the channel ΔT because channel outlet = boiler inlet and boiler outlet = channel inlet.

As the temperature in the steam generator falls from 266°C to 250°C, the pressure falls from 5.17 MPa(a) to around 4 MPa(a). This falling pressure of steam flow is entered into the boiler pressure control program.

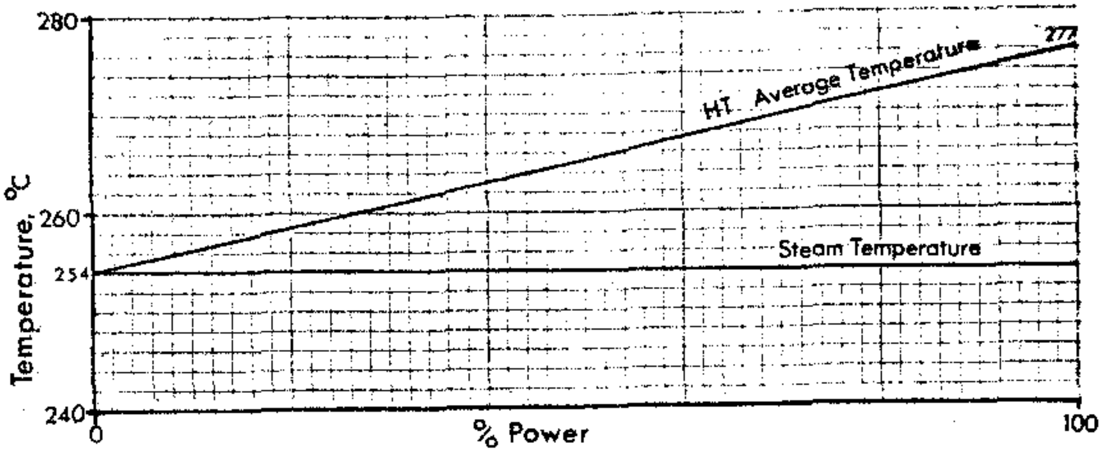


B.1.8

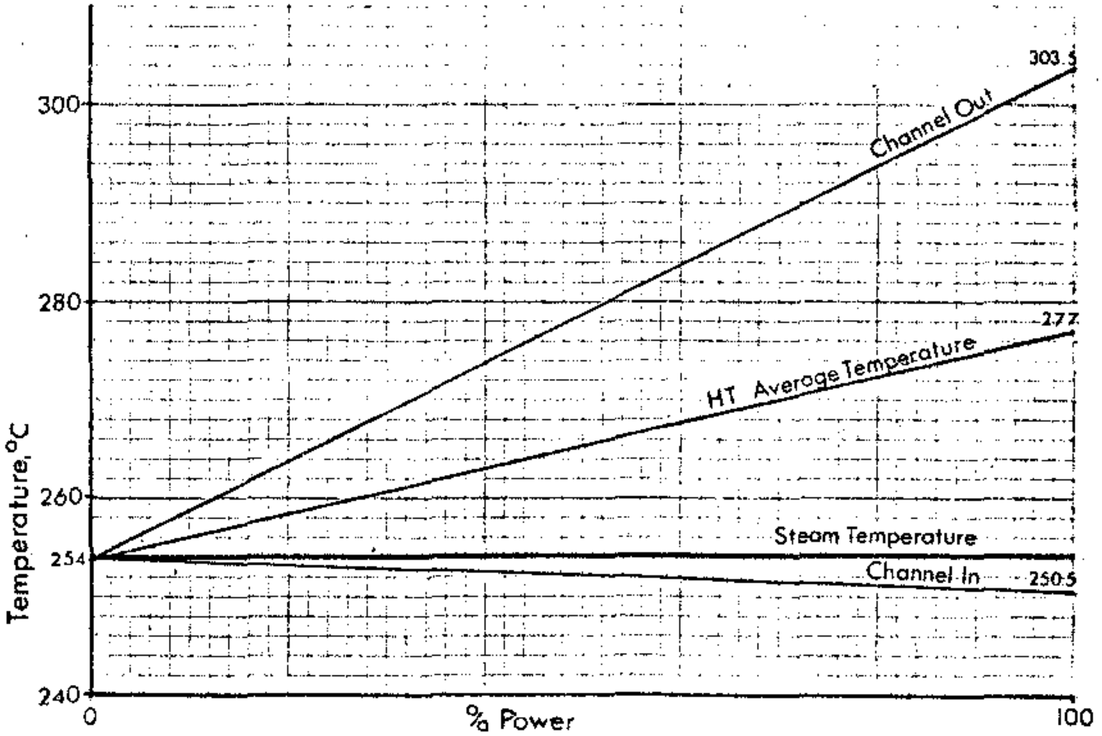
At zero power when the steam generator and reactor are at operating temperature, the average heat transport temperature and the steam generator temperature will be sensibly equal. If the steam generator pressure is 4.25 MPa(a), then the temperature is 254°C. At this condition, the heat transport average temperature is also at 254°C.

B.1.9

At BNGS-A, 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 heat transport fluid and the steam generator. In addition, the average temperature of the heat transport fluid must be higher than that of the steam generator. This is shown in the diagram where the average heat transport temperature leaves the steam temperature at 254°C and rises to a higher value around 277°C. The important point to note is that the average H.T. temperature rises - you couldn't determine that the H.T. temperature was 277°C. This is complicated by the arrangement of inner/outer zones with the heat transport precoolers.



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.



These figures have been simplified to show the trends. The design channel inlet temperature for the inner zone is 250.5°C and 265°C for the outer zone. At full power, the design channel outlet temperature is 304°C. These values have been modified to operate the reactor with no boiling in the channels.

B.1.10

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, thermal inequilibrium occurs and the PHT average temperature starts to rise.

As the level in the steam generator falls below the top of the tube bundle, heat transfer is further reduced due to the reduce heat transfer surface area available and the PHT system average temperature rises faster than before.

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

B.1.11

At PNGS-A, the high pressure trip on the heat transport system occurs at 9.55 MPa(a).

At BNGS-A, the heat transport high pressure trip occurs at 9.66 MPa(a).

B.1.12

A high pressure in the heat transport system will normally result from a high temperature. This condition will arise when there is an imbalance in the rate at which heat is being produced by the reactor and the rate at which heat is rejected in the steam generator. More specifically, if the temperature is rising in the heat transport system, it is because the steam generator is not removing heat from the heat transport system at the same rate. This situation may arise in the event of loss of feedwater to the steam generator when the rate of heat transfer will rapidly reduce and result in an increased H.T. temperature and pressure.

This may occur if the reactor power exceeds the heat capacity of the steam generator. Such a condition may arise due to a loss of reactor power regulation. In this case, the heat transport flowrate is unchanged but the total heat has increased beyond the capacity of the steam generator and results in an increase of heat transport temperature and pressure.

A loss of H.T. pressure control may also result in a high pressure in the H.T. system.

The steam generator is unable to act as an effective heat sink if the heat transport flowrate decreases. In this situation, the reactor power has to be removed by a reduced mass flow which means that the heat transport averages temperature and therefore, pressure rises.

The two major problems of a low heat transport pressure concern the effect that vapour production within the D_2O has on (a) Heat Transport Pumps, and (b) Fuel in the Channel.

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

If the heat transport pressure drops to the saturation pressure corresponding to the heat transport temperature, vapour will be produced in the fuel channel. If large scale voiding 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 which will produce fuel sheath failure and fuel damage if not prevented.

B.1.13

At PNGS-A, the reactor design was such that the volume of the primary 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 when compared to PNGS-A:

a) the average heat transport temperature rises by some 27°C.

b) boiling was designed to occur in the fuel channels, but operating limitations have resulted in reactor operation with no channel boiling.

There is a significant increase in heat transport volume as the power is increased from 0% to 100%. The increase in volume amounts to 17 m^3.

B.1.14

As we have already seen, the volumetric expansion of the heat transport system at PNGS-A, when at power, is not very large.

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

If low pressure exists in the heat transport 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 BNGS-A, the change in heat transport volume with power is much larger than at PNGS-A and exceeds the rates of change which could be handled easily with a feed and bleed system alone.

The heat transport 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 heat transport 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 heat transport 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 heat transport pressure.

B.1.15

At both PNGS-A and BNGS-A, a high level in the vessel controlling reactor pressure is taken as an indication of loss of ability to control the heat transport pressure.

The heat transport system is expanding at a greater rate than can be handled by the pressure control circuit.

In the short term, the only way that the heat transport system volume can contract instead of expand is as a result of the temperature being reduced, either by increased steam flow or a reduction in reactor power.

At PNGS-A, a high level in the bleed condenser will initiate a reactor setback. A major problem with the bleed condenser is that as soon as the vapour space disappears, the condenser will go solid. At this point, the pressure will rise rapidly and there is a danger of rupturing the bleed condenser. Bleed condenser relief valves discharge into the boiler room to prevent the rupture of the condenser.

At BNGS-A, *the inability to control reactor heat transport* pressure as seen by a high level in the pressurizer, also results in a reactor setback.

B.1.16

As discussed in the previous question, the rise in level in the pressure controlling vessel is the result of an inequilibrium between the expansion rate of the heat transport fluid and the bleeding rate of the pressure control system.

We can restore this equilibrium by reducing the temperature of the heat transport system. This may be done by two methods:

a) *removing more heat from the heat transport fluid.*

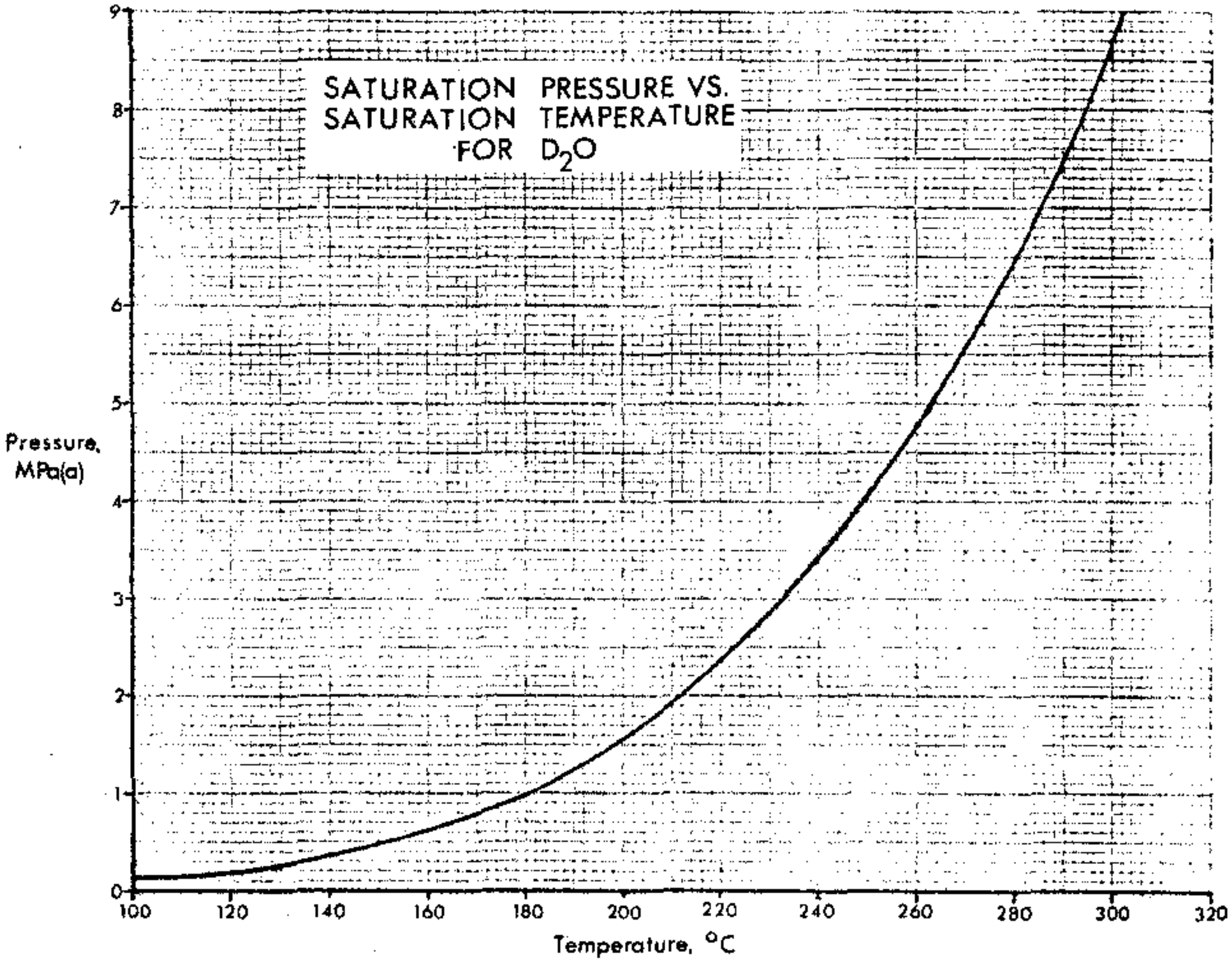
b) producing less heat in the reactor.

If the turbine is at full load, steam may be rejected from the system via the steam reject valves or the steam discharge valves. This action will produce a significant increase in the heat sink capacity to the reactor and quickly reduce heat transport temperature.

A reduction in reactor power will produce the same effect. The time taken will depend upon the setback rate that is input. This is the normal reaction.

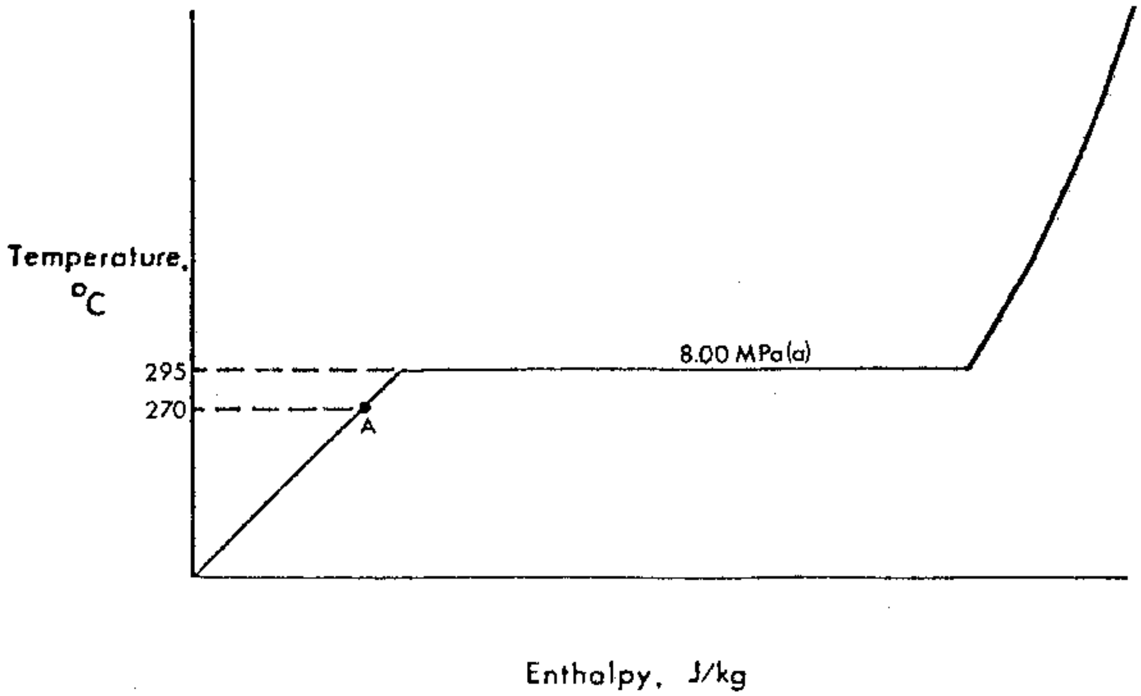
The effect of opening a large steam valve will cause the heat transport fluid to shrink at a greater rate than can be matched by the heat transport pressure control system and the temperature will fall. As soon as the pressure reaches the saturation value, the heat transport system will start to boil and cause voiding in the fuel channel.

The operator must closely watch that the heat transport pressure does not reach the saturation pressure if channel voiding is not to occur.



The graph of saturation pressure/temperature is useful to compare actual heat transport pressure with the saturation pressure corresponding to the H.T. temperature. The actual H.T. pressure should always be higher than the saturation pressure.

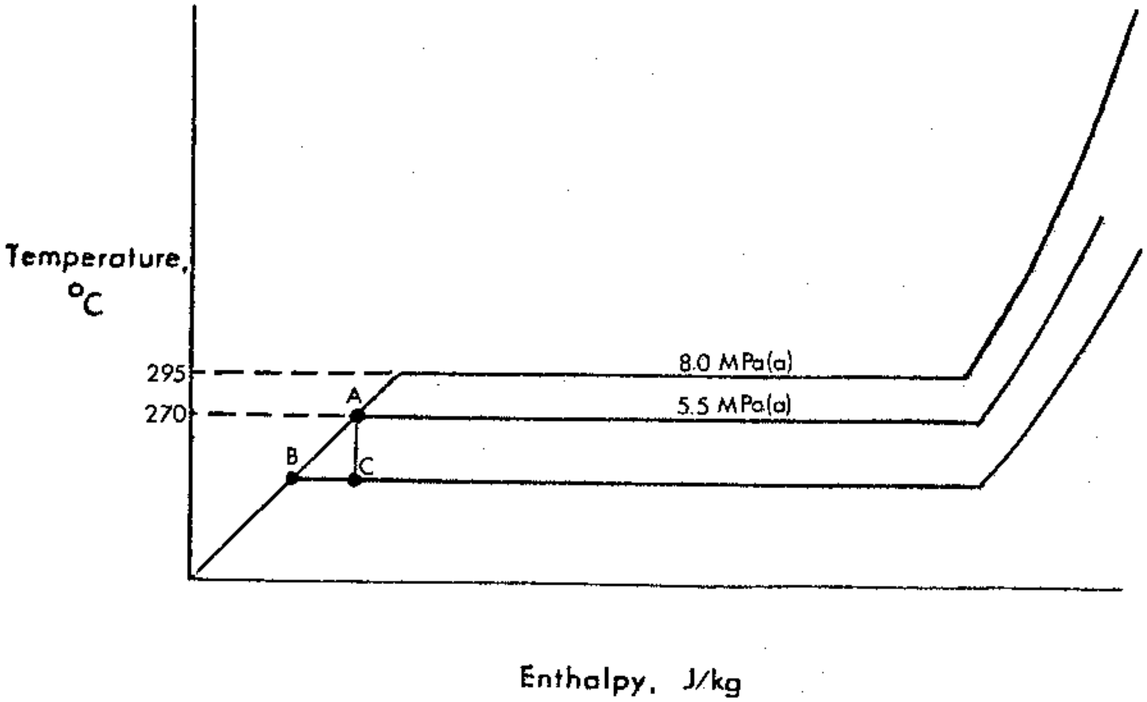
B.1.17



At 8.0 MPa(a) from steam tables, the saturation pressure is 295°C. The actual temperature of the heat transport liquid is 270°C which means that it is subcooled by 25°C.

B.1.18

When the pressure has fallen to 5.5 MPa(a), the corresponding saturation temperature is 270°C. This is also 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.



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

1. saturated liquid at point B.
2. vapour generated with the enthalpy B-C. You can see that for saturated liquid, the enthalpy at B is less than that at A.

B.1.19

The main concern with channel voiding is 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 zircalloy 4 has a melting point of around 1800°C, sheath failure is likely to occur between 800 - 1100°C.

Loss of fuel containment and the release of fission products are major considerations that depend upon 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 as occurs when the channel is voided, could result in a fuel meltdown if no action was taken.

B.1.20

When the liquid coolant has reached the saturation temperature and vapour is about to be produced, the temperature rise will stop. From this point on, we have little idea of what is actually happening in the channel with respect to boiling. There may be 8% or 80% vapour being produced.

As power is increased, more vapour is produced at constant temperature. The channel ΔT is no longer an indication of channel power.

B.1.21

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

a) a reduction of coolant flow.

b) a loss of 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 and channel voiding occurs. Once vapour production starts, the coolant temperature remains constant.

If the pressure falls to the saturation pressure corresponding to the temperature of the heat transport coolant, *vapour production will begin and again, channel voiding will* result. 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 overheating has commenced.

B.1.22

The loss of coolant may still be contained within the system, eg, the D_2O may be leaking into the boiler or the loss of coolant may be leaving the system due to leak in the circuit.

A low level in the D_2O storage tank may be an indication of loss of coolant from the heat transport system.

A loss of heat transport pressure may also be an indication.

If the leakage is external and large as in a LOCA as opposed to a leak, high boiler room pressure trip and Beetle alarm would indicate leakage of D_2O or steam.

B.1.23

If the leak is large enough that the heat transport system pressure starts to fall, then channel voiding will occur at the saturation pressure. At this point, the rate of pressure decrease will reduce and the rate may even be zero as vapour is produced in the channel.

Also, at this point channel, voiding is established and fuel heat transfer is dramatically reduced.

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

The reactor is crash cooled using the steam reject/discharge valves. This exercise reduces the heat transport system pressure and temperature in a few minutes.

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

B.1.24

The basic difference between a large leak and a massive loss of coolant is the time taken for the system pressure to fall. In a large leak situation with crash cooling, the time scale is in the order of minutes. With a massive loss of coolant, the crash cool exercise 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 voiding of the channel 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 degrees 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 will not become unsafe due to loss of coolant.

B.1.25

At PNGS-A, the emergency injection system uses moderator D_2O. Consequently, injection cannot occur until the heat transport pressure has fallen below the moderator pump discharge pressure.

At BNGS-A, the emergency injection is by gravity feed from a dousing tank in the top of the vacuum building. The injection cannot occur until the heat transport pressure drops below the static head of the tank.

A pressurized tank is currently being installed at BNGS-A to speed up the emergency core injection process.

B.1.26

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 PHT pump.

This condition will prevail with no pumps running, provided that the thermosyphon is not lost. The thermosyphon may be lost if vapour or gases collect in the top of the tubes in the steam generator.

The ROH temperature is monitored to ensure that it does not reach the saturation value when vapour would be produced. ROH 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.

J. Irwin-Childs