Reactor, Boiler & Auxiliaries - Course 233

HEAT TRANSPORT D_2O AND HEAT TRANSPORT MAIN SYSTEM

I. HEAT TRANSPORT D_2O FEATURES

There are some important features of the HT D_2O that are discussed below:

1. HT isotopic.
2. HT activation products.
3. HT pressure and temperature.

(HT chemical control is not dealt with in this lesson but is included in chemistry courses, and in this course in the section on the HT purification system.)

1. HT Isotopic

(i) Acceptable Range

It is not as important in the HT system to have the isotopic as high as that in the moderator system. In practice the isotopic is kept above ∿97.5% in our plants.

Figure 1 shows typical HT isotopic values for the Pickering NGS-A units from 1973. As with the moderator D_2O the isotopic is directly related to the reactivity and hence to fuel costs (see Table 1).

TABLE 1

HT System Isotopic Data

Change in D_2O	±1%
Δk Change	±0.5 mk
Fuel Cost Penalty*	$90,000/year

* Zero Penalty taken for 99.75% D_2O.

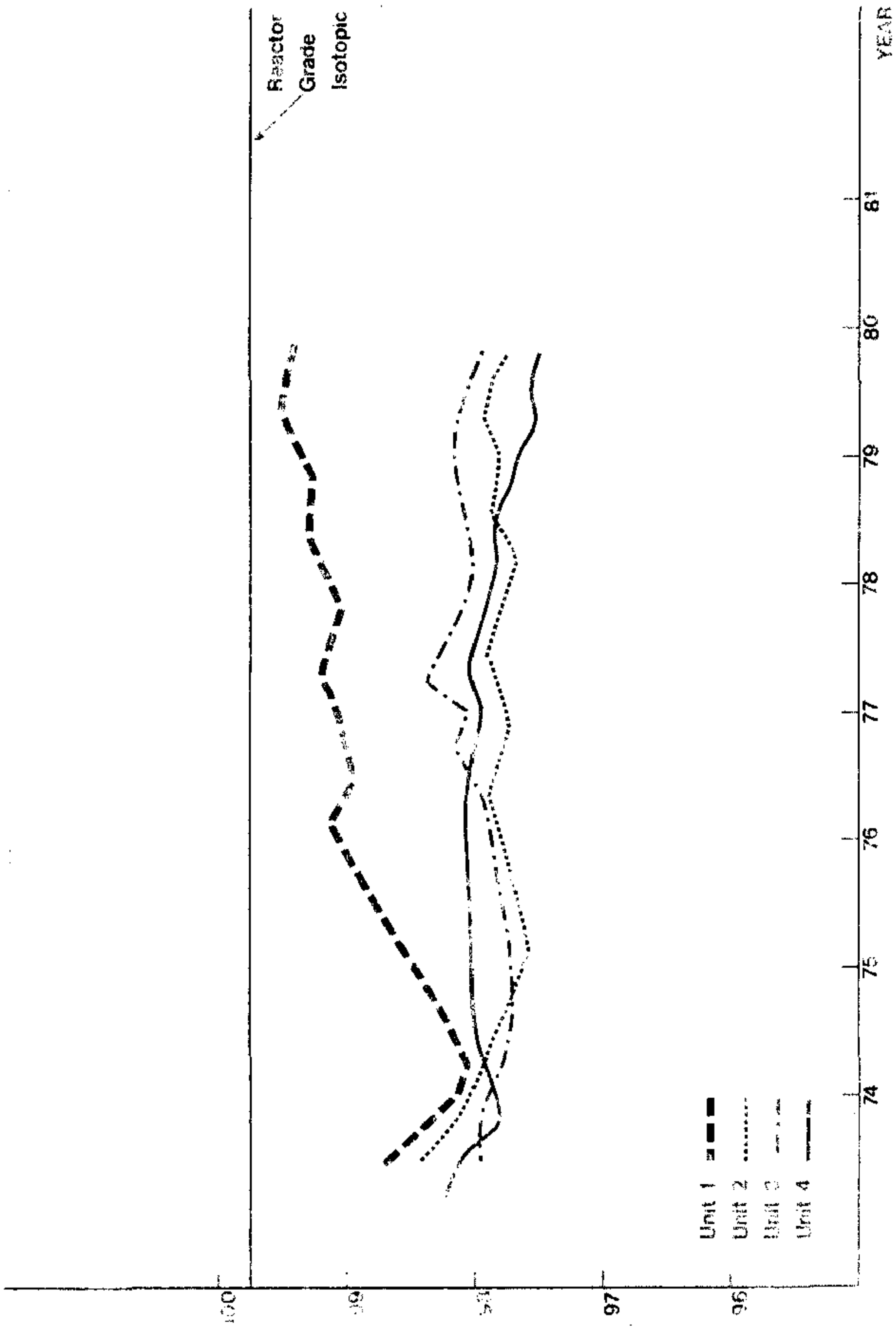

Figure 1: Pickering HT Isotopics

Comparing this table to the equivalent table for moderator D_2O (section 20-1), it is seen that the fuel cost penalty per percentage downgrading is much smaller for coolant than it is for moderator. A simple reason for this is that the HT D_2O volume in core is much less than that of the moderator D_2O volume in core. Hence the HT D_2O does not contribute as much to neutron absorption as does the moderator D_2O.

As far as reactivity is concerned the HT isotopic could probably drop as low as $\sim$90% and criticality still be maintained, depending on the core excess reactivity and available reactivity from adjuster rod withdrawal. However, the actual lower limit is usually fixed higher than this (at $\sim$97% for Bruce A), the specific figure for a given station being quoted in Station Operating Policies and Principles. The reason for this is reactor safety in case of a large loss of coolant accident. Because a positive increase in reactivity results when the HT D_2O is lost, the lower the HT isotopic the more positive this increase will be. The reason this occurs is that both the factors p and f in the four factor formula (see 227 notes) for k, the multiplication constant, increase on a LOCA.

The acceptable increase in reactivity on a LOCA then puts this limit on the HT isotopic. (For the same reason addition of chemical poisons to HT D_2O, which changes f, is prohibited.)

As far as reactor operation is concerned, there is no upper limit on HT isotopic, which can be increased as desired by make-up with higher isotopic D_2O from the HT upgrader.

In practice the limit is set by two economic factors:

(a) the higher cost of HT D_2O upgrading as the isotopic increases.

(b) the lower cost of fuelling due to the higher burn up as isotopic increases.

Table 2 summarizes the effects on reactor operation of changing the HT isotopic, to illustrate the practical importance of the points discussed above.

Change in HT isotopic from operating value of between 97 - 100%	Immediate effect on reactor at full power operation.	Long term effect on reactor at full power operation.
I. Isotopic slowly increasing due to virgin or upgrader D_2O additions for make-up (Typical max ∿0.05%/month.)	No observable effect, isotopic change too small.	Fuelling rate (bundles/week) reduced slightly. Higher average fuel burn up.
II. Sudden downgrading by ≲3% to the lowest isotopic allowed by Operating Policies & Principles.	Operation continues with a drop in average liquid zone level, (adjuster(s) possibly out).	Increased fuelling rate needed to return (and maintain) zone levels/adjusters to normal operating positions. Lower average fuel burn up.
III. Sudden downgrading to below the limit in II.	As above, unless drop in Δk is large enough to shutdown reactor.	Reactor should be shut down until minimum HT isotopic is available.

TABLE 2

(ii) Mechanisms by Which HT D_2O Can Become Downgraded During Normal Operation

It is of interest to note the processes by which HT D_2O can get downgraded during normal operation. The modes of H_2O ingress are:

(a) H_2 gas addition system (see HT H_2 Addition).

(b) H_2O from air inleakage into the HT D_2O collection system (see HT D_2O Collection).

(c) H_2O from air inleakage into the HT D_2O storage tank.

(d) accidental additions of downgraded makeup or downgraded collection returns.

Sources (a) to (c) will produce a small but continuous downgrading while source (d) will be infrequent, but possibly large.

2. HT Activation Products

(i) Nitrogen-16, Oxygen-19

The production modes and consequences of these isotopes are essentially the same as those discussed under moderator activation products and so will not be repeated here.

(ii) Tritium

The production and consequences of HT tritium are the same as those discussed in the moderator section. The important difference is that the theoretical equilibrium activity of HT tritium corresponding to Figure 2, will be $\sim$2-3 Ci/kg, much less than moderator equilibrium activity for the reasons already discussed in 20-1.

The actual tritium buildup is shown in Figure 3, for PNGS-A since 1971. The straight line shows the average for unit 1 up to 1977. From 1977 until late 1978 the results of the tritium displacement program are evident in the decreasing tritium concentrations of all units, in particular in unit 4, where virgin D_2O was used for make-up. The other units took make-up from unit 4 during this period. During 1975 the increases in tritium illustrate the fact that upgraded tritiated D_2O was being used for make-up, again unit 4 showing the largest effect. The HT tritium concentrations are being maintained below 2 Ci/kg by D_2O

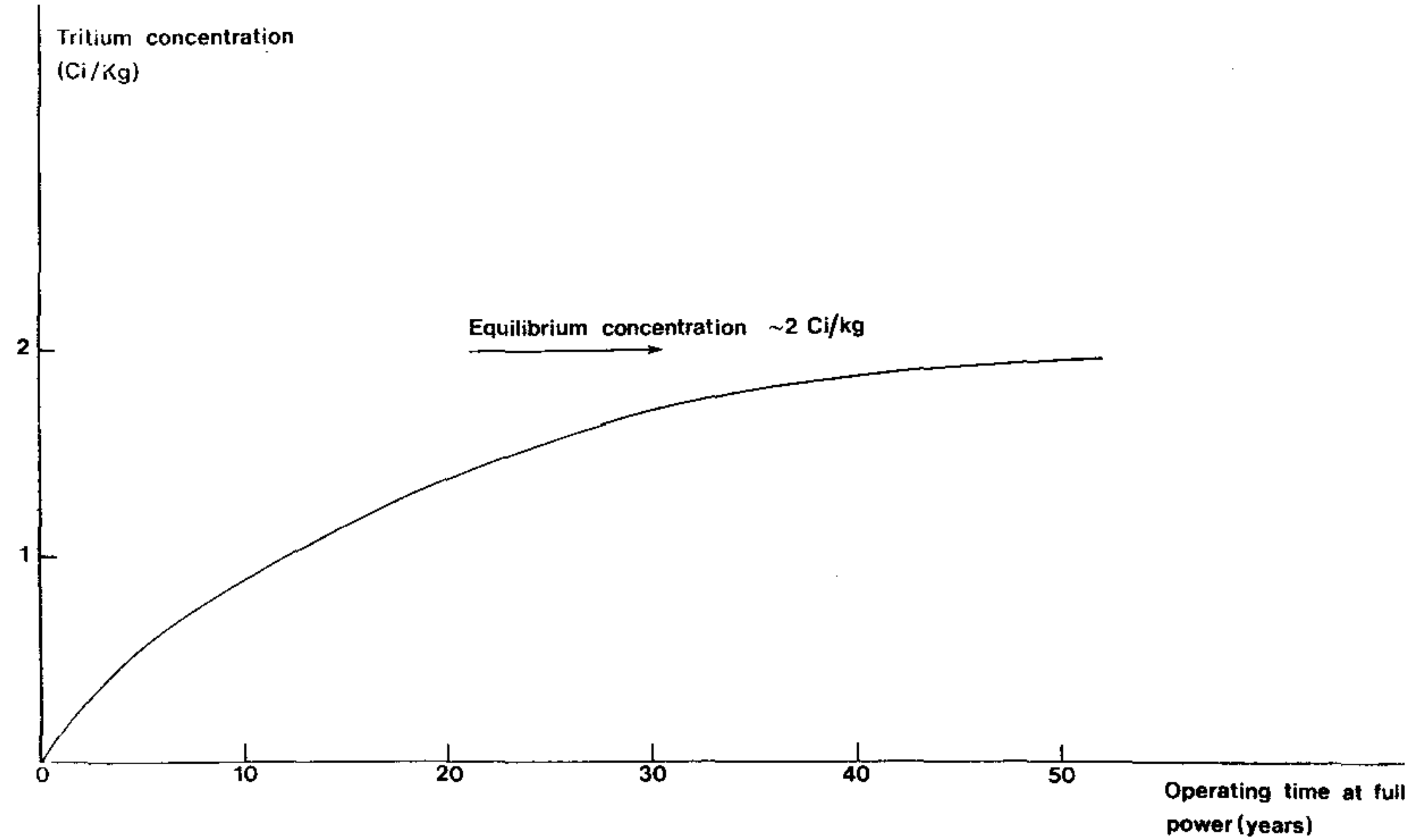

Figure 2: HT Tritium Buildup at Full Power (No Make-up)

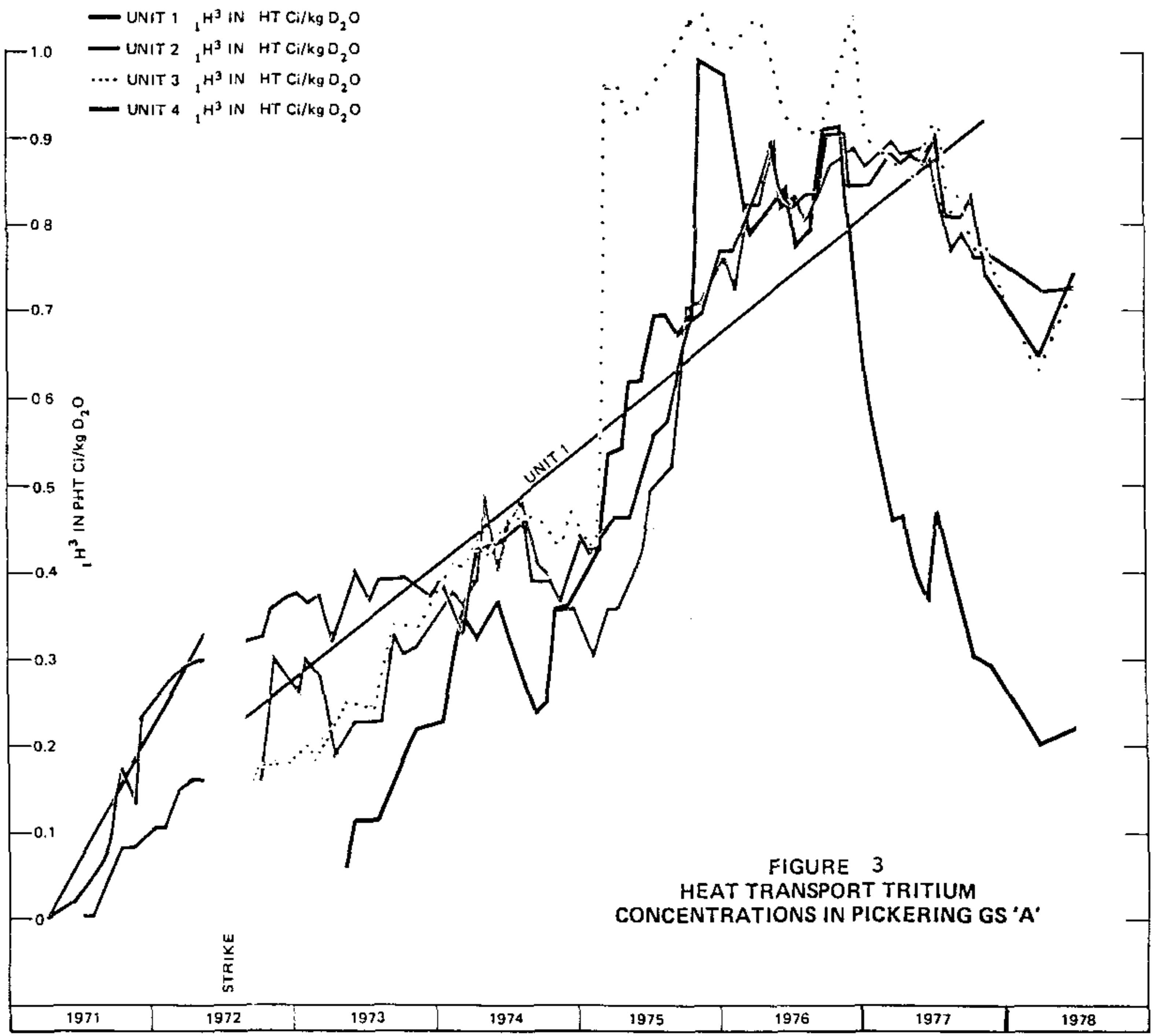

FIGURE 3
HEAT TRANSPORT TRITIUM
CONCENTRATIONS IN PICKERING GS 'A'

management, this being the currently acceptable maximum. This value is well below the tolerable tritium concentration in the moderator, as the HT system operates at a higher pressure and contains more leakage points than the moderator system, and therefore produces more leakage during normal operation than the moderator system.

3. Heat Transport Pressure and Temperature

(i) Pressure

The heat transport system is pressurized to prevent boiling. The maximum allowable operating pressure is dictated by the thickness of the pressure tube walls - the thicker these walls, the higher the maximum permissible pressure. But the thicker the pressure tube walls, the greater is the parasitic neutron absorption, and hence the lower the fuel economy. Fuel economy is deemed acceptable with a pressure tube wall thickness of about 4 mm. This thickness allows an operating pressure of up to about 10 MPa while still maintaining an adequate safety margin against tube rupture.

Coolant pressure is controlled to a set point, at the outlet headers, by the pressure control system, see Pressurizing System.

(ii) Temperature

The higher the coolant temperature, the higher the boiler steam temperature, and the more efficient the thermal-to-electrical energy conversion for a fixed condenser temperature. Thus it is desirable to operate with the highest possible coolant temperature. Clearly this temperature must be kept below the saturation temperature at the operating pressure if boiling is to be prevented. There are some station differences however, discussed below.

At Pickering the coolant is maintained below boiling point in all channels, and heat transport boiling is prevented by a reactor trip on high temperature in the outlet headers. The trip set point is below saturation temperature.

At Bruce however, a few percent boiling is tolerated at the outlets of certain designated channels. Nucleate boiling (small bubbles) actually increases heat transfer from the fuel to the coolant. However, should boiling increase to the extent that a film of steam separates the fuel from the coolant (film boiling), heat transfer falls drastically and fuel temperature rises sharply. This extremely hazardous condition is called 'dryout' or 'steam blanketing'. Clearly where nucleate boiling is tolerated, the margin to dryout is reduced.

Note that coolant temperature is not controlled directly, as is pressure. Rather, coolant temperature is controlled indirectly by the boiler pressure control program which sets boiler temperature by controlling boiler pressure (see Steam Supply Systems). For a particular reactor thermal power, the average boiler temperature will 'control' the average heat transport temperature.

Reactivity Effect of Heat Transport Temperature

The heat transport D_2O temperature has an important effect on the core reactivity. From Nuclear Theory, the coolant temperature coefficient of reactivity is positive.

However, in practice, the reactivity effect which is observable (and hence of interest to the operator) is the net effect due to temperature changes in both fuel and coolant. This is so because a temperature change in the fuel will always lead to a corresponding coolant temperature change, and vise versa. The net effect is a negative reactivity change as the temperatures of fuel and coolant increase.

Examples of where this reactivity effect affects reactor operation are:

(a) Warmup and Cooldown

The reactivity change as the coolant warms up from $\sim$60°C to $\sim$250°C will be typically a few mk negative and will have to be supplied by the controlling reactivity mechanisms as the heat transport system warms up.

(b) Power Maneuvers

The total reactivity change as the reactor power is raised from the hot 'zero' power shutdown state to 100% full power is defined as the power coefficient of reactivity. The reactivity change again will be typically a few mk negative. As power increases, this reactivity will have to be supplied by the controlling reactivity mechanisms.

The heat transport temperature reactivity effect is an advantage from a reactor safety viewpoint, because a power increase inserts negative reactivity, ie, the reactor has a natural tendency to self stabilize power. In practice, however, the small negative reactivity supplied cannot be relied upon to prevent or terminate a power excursion. The reactor regulating system is still required to control the reactor power at the desired setpoint by manipulating liquid zone levels, for example. The ultimate protection against power excursions is supplied by the various neutronic trips used (eg, high lin N, high lin N rate, high rate log N).

II. THE MAIN HEAT TRANSPORT SYSTEM

The purposes of the main HTS are:

1. To transport reactor heat to the boilers, where it produces steam to drive the turbogenerator, and

2. To cool the fuel at all times, even when the reactor is shut down.

93% of the heat produced in a reactor operating at 100% full power comes from the fission process directly, 6% from the decay of fission products, and 1% from the PHT pumps. Note that, up to 7% full power still has to be removed after shut down - hence purpose #2 above. A more detailed discussion of heat sources, reactor power rundown, and heat transfer paths is given in Heat Sources and Transfer Paths.

All large CANDU reactors have a figure-of-eight HT loop (see course 433) with banks of pumps and boilers on both sides of the core, as shown in Figure 4. This symmetrical arrangement of pumps and boilers facilitiates bidirectional coolant flow in the core. Typical temperatures and pressures at full power are indicated on Figure 4 at key locations (inlet and outlet headers, boiler outlet) for reference. Figure 4 actually shows two HT loops, effectively connected in parallel via motorized isolating valves joining the reactor outlet headers. Plants such as Pickering and Darlington have this arrangement, which has the safety advantage that, on a LOCA, these valves close to isolate the two loops from each other. This then limits the loss of HT D_2O to only 50% of main system volume, assuming the LOCA is due to piping failure in one loop only. Only one pressure control system is needed, even with two HT loops, because during normal operation, both loops are tied together with at least one of the interconnect valves open.

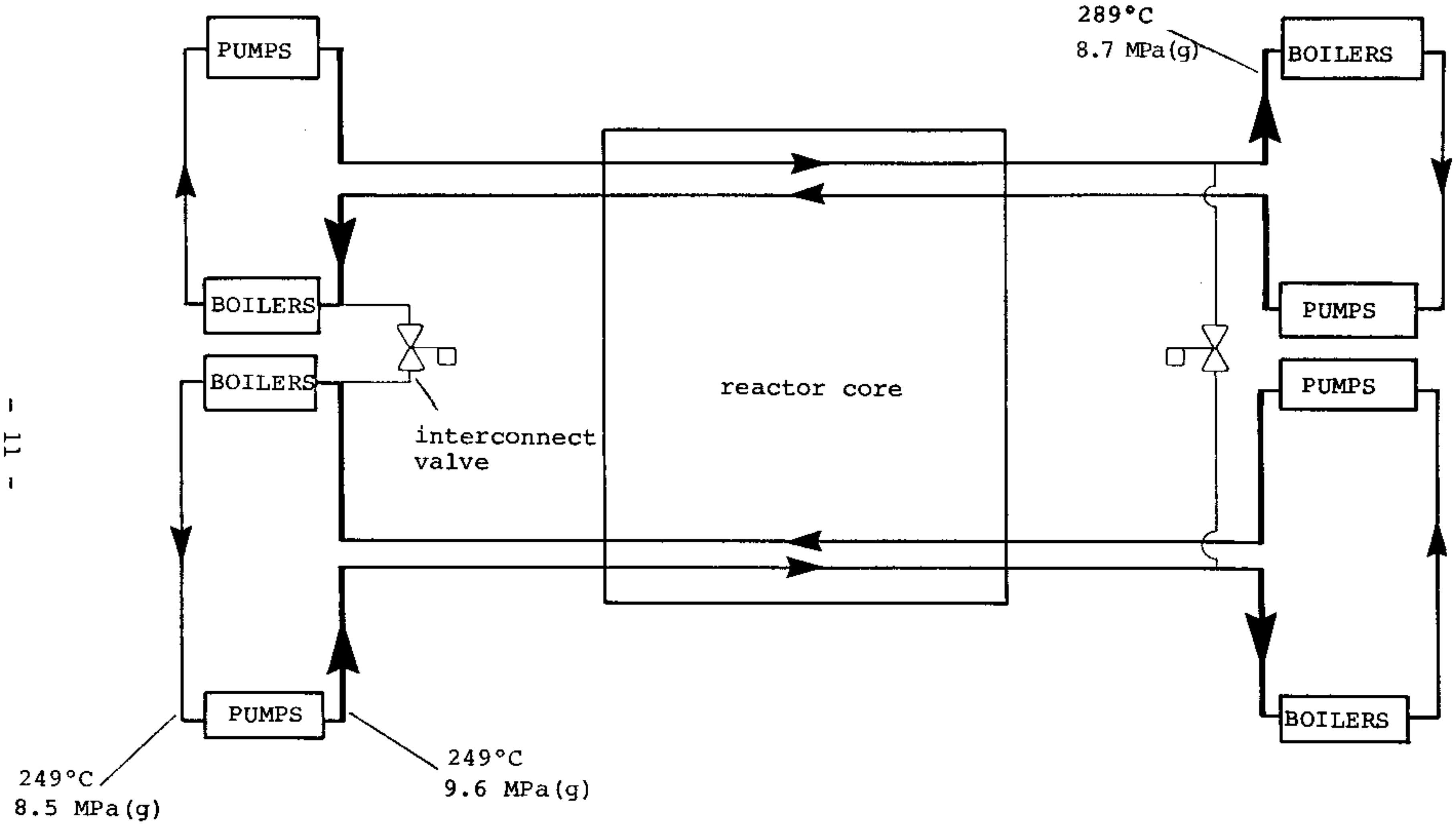

Figure 4: Double Loop HT Main Circulating System (Pickering NGS)

All channel inlet temperatures and all channel outlet temperatures are essentially the same in this arrangement. In order to obtain approximately equal channel outlet temperatures, since the central channels produce more power than outer channels, the channel flow is designed to be larger in the central channels. This is done by sizing the feeder pipes to produce the desired flow rate in each channel.

A major variation from the HT system design of Figure 4 is used on all Bruce reactors. A feedwater preheater external to the boiler was introduced into the HT loop, Figure 5. The Bruce boilers are not equipped with internal preheaters, as they are at Pickering, see Steam Supply System, Figure 2. Only a single HT main loop is used, and a preheater is located just after the main pumps. A portion of the HT D_2O flows through the preheater and into the inner-zone[(i)] channels of the core. The remainder of the inlet HT D_2O is directed around the preheater to the outer-zone channels of the core. The function of the preheaters is to preheat boiler feedwater using heat extracted from the HT D_2O.

Typical full power temperatures of the HT D_2O at the preheater inlet and outlet are shown in Figure 5. Note that the preheater serves to precool the inner zone HT D_2O. The inner zone HT inlet temperature is $\sim$251°C compared to the HT outer zone inlet temperature of $\sim$265°C. Both inner and outer zone outlets combine into a common outlet header at a common temperature of $\sim$ 304°C. Channel flows in this type of system are arranged to be nominally the same for all channels. Thus the inner zone channels produce a higher power as a result of the higher channel ΔT's: $\sim$53°C compared with $\sim$39°C for outer channels. Thus use of separate preheaters at Bruce achieves the same objective of extracting more power from central channels as use of varied sizes of feeder pipes does at Pickering and Darlington.

(i) This consists of the central 280 channels and is not related to the liquid control 'zones'.

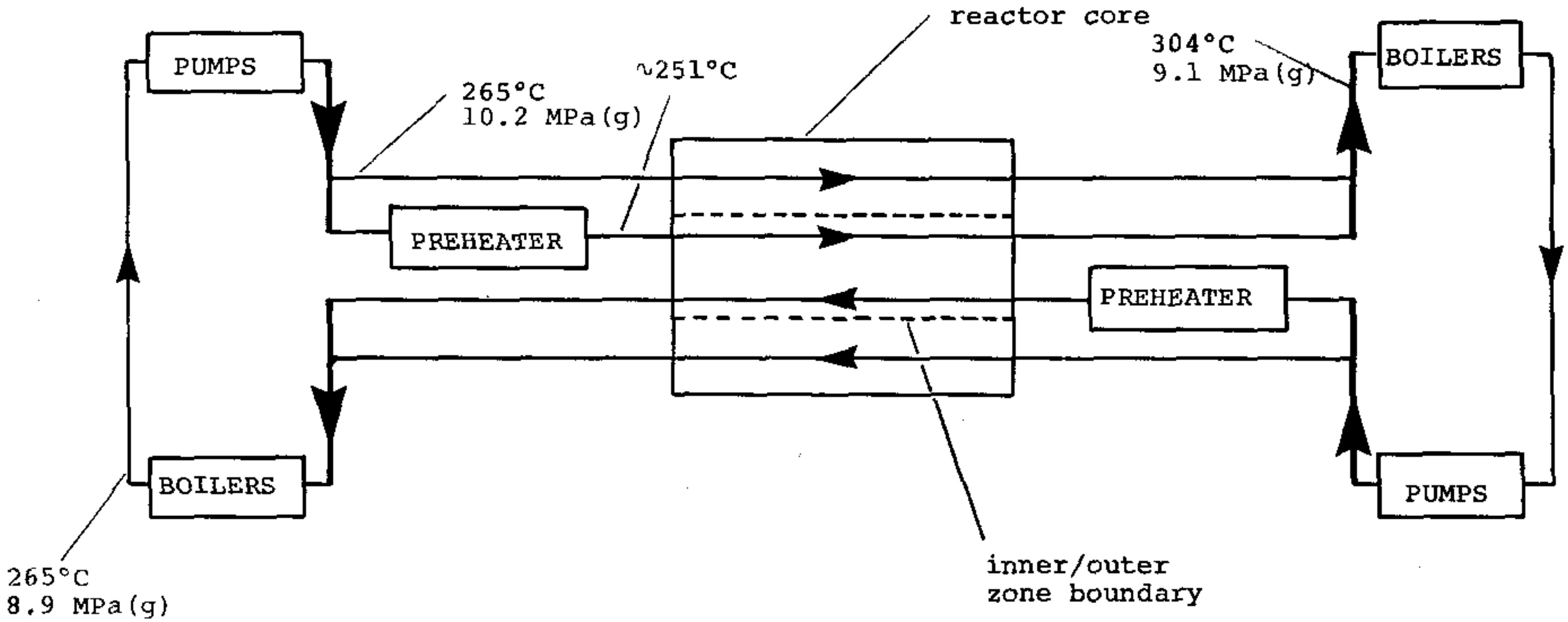

Figure 5: Main HT System Incorporating Preheater Design (Bruce NGS)

III CONNECTIONS BETWEEN HTS AND AUXILIARY SYSTEMS

There are many auxiliary systems connected to the main HT system. In a course of this nature it is not feasible to specify all the various tie-in points, but a simplified illustration is given in Figure 6. Most of the systems shown in Figure 6 are discussed in subsequent chapters of this course, where more details can be found.

The connections not discussed in subsequent lessons are those to the activity monitoring system, high pressure test supply lines and the instrument lines.

The activity monitoring system consists of small lines, one from each channel outlet feeder, leading to the failed fuel location system. This system allows identification of individual channels containing failed fuel. The high pressure test supply lines are small lines used to provide a reference measurement of HT high pressure for various systems which have high or low pressure alarms or trips, eg, SDS1, SDS2, ECCS. In addition, numerous other direct instrument connections exist to measure parameters such as flows and pressures, at various locations in the system.

The important point to realize regarding all these connections to the main HT system is that the integrity of the HT system pressure boundary is dependent on these connections remaining intact. Rupture of any of these connections will result in loss of HT D_2O from the main system. The extent of the coolant loss will vary, of course, according to the size of the ruptured connecting line and the pressure and normal flow rate of the HT D_2O at the break location. Figure 6 lists the connections in order approximately according to their size.

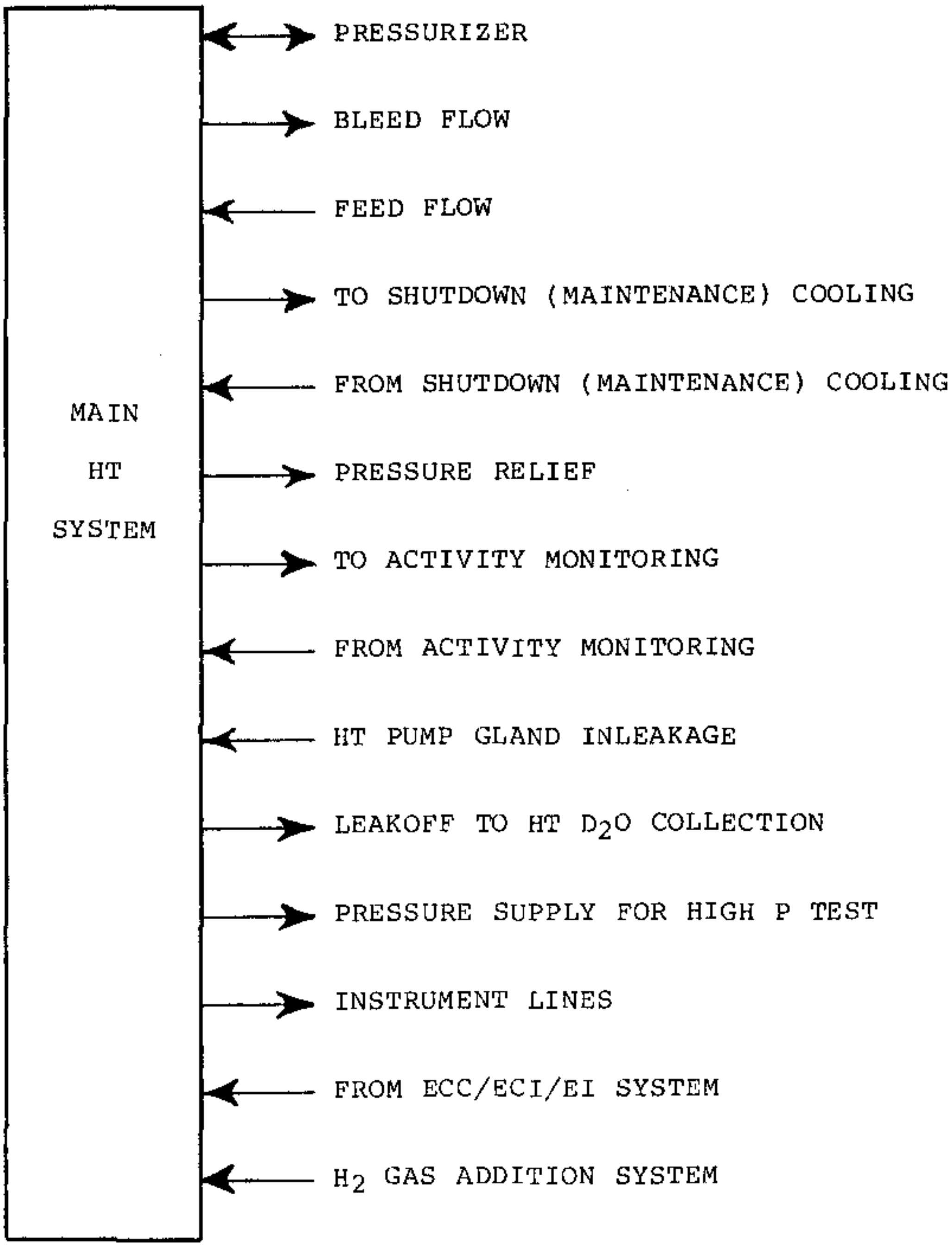

Figure 6: Simplified Illustration of HT Main System Interconnections with Other Systems

ASSIGNMENT

1. State the acceptable operating range of HT isotopic.

2. State what effect HT temperature has on reactivity. When is this effect important?

3. State the HT main system heat sources (as a % of total) with

   (a) the reactor at full power

   (b) the reactor shutdown.

4. The reactor outlet header temperature and pressure were quoted to illustrate how close to boiling the HT D_2O is. Would measurements of temperature and pressure at the reactor inlet header give a better indication of how close the HT D_2O is to boiling (ie, the margin to boiling)? Explain.

5. For your own plant specify the tie-in locations for the auxiliary systems shown in Figure 6. State any exceptions to the system list of Figure 6.

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