Reactor, Boiler & Auxiliaries - Course 233

# HEAT SOURCES AND TRANSFER PATHS

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## I. HEAT SOURCES IN THE MAIN HEAT TRANSPORT SYSTEM

### (a) Reactor at Full Power

Ninety-three percent of the heat produced in a reactor operating at 100% power comes from the fission process directly, about 6% from the decay of fission products, and about 1% from the HT pumps. Whereas the fission and decay heat sources are localized in the fuel, the pump heat source is distributed around the whole HT circuit, because it is essentially heat generated by friction as the coolant is forced around the loop. Figure 1 illustrates the full power heat sources in the HTS.

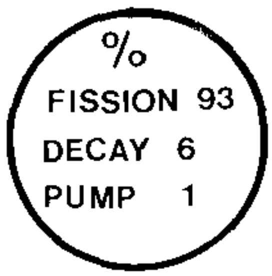



Figure 1: Full Power Heat Sources in the HTS.

### (b) Reactor Shut Down

Figure 2 shows the power rundown curve following a reactor trip at time zero. Note that the fission power decays to negligible values after a minute or so, whereas the fission product power decays relatively slowly - to about 3% full power after 3 minutes, to about 1% full power after 8 hours, and so on. Note that HT pump heat

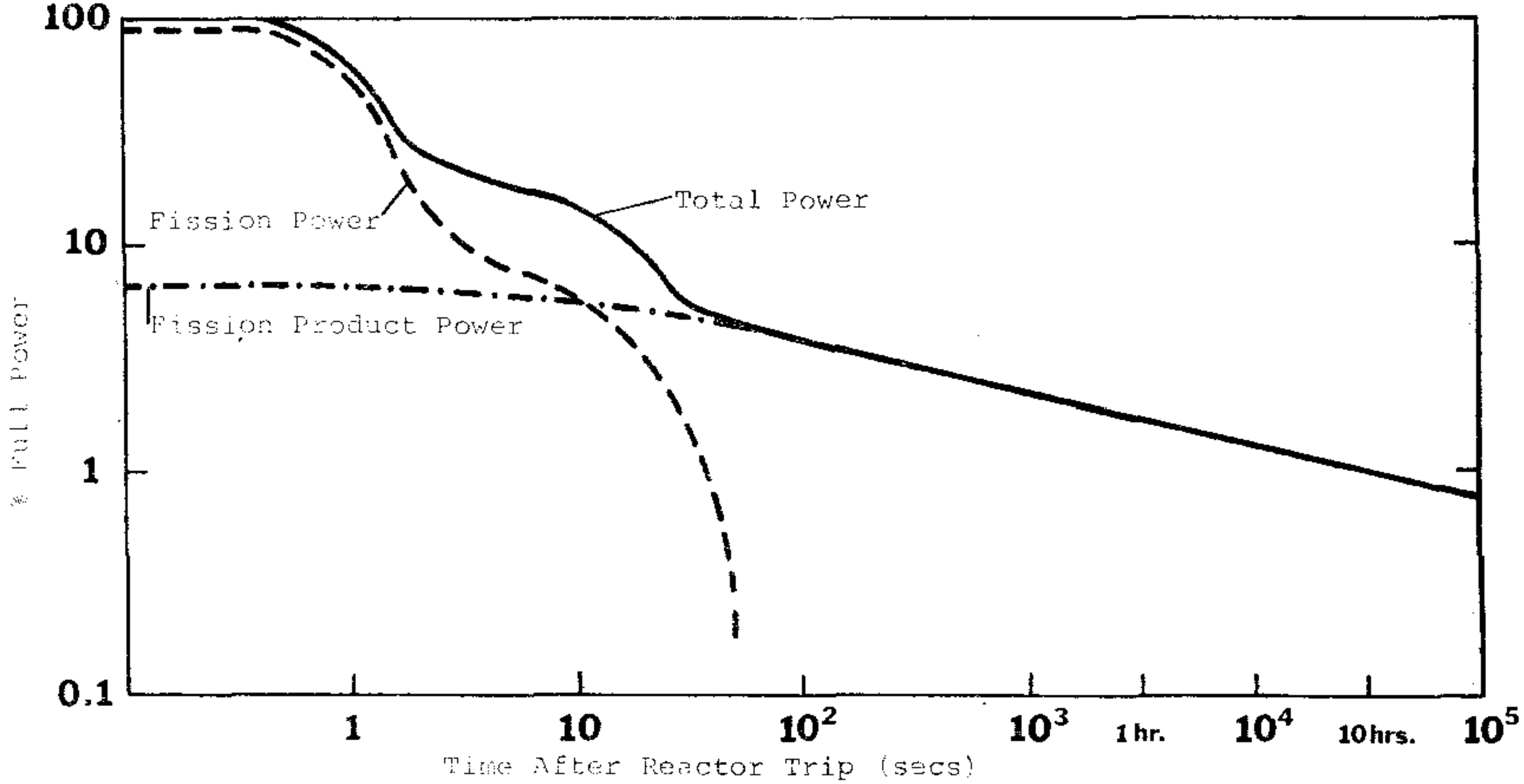



Figure 2: Power Rundown After Reactor Trip.

is not included in Figure 2, but that the pumps continue to contribute about 1% full power as long as they are running. The shutdown heat sources in the HTS are shown in percent full power in Figure 3 below (a) one minute after shutdown and (b) 8 hours after shutdown, assuming that the HT pumps are still running.


(a) One Minute After Shutdown (b) 8 Hours After Shutdown

Figure 3: Shutdown Heat Sources in the HTS

Example:

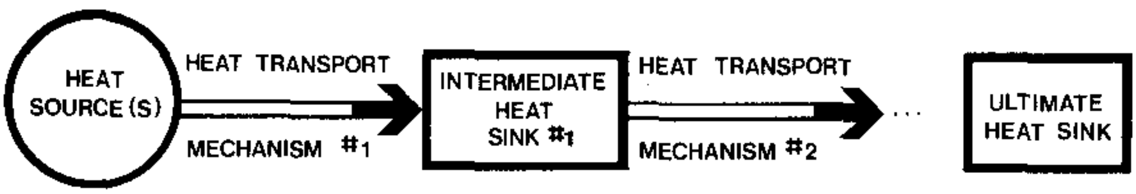
For a Bruce NGS-A unit, 100% thermal power = 2392 MW(th). The fission, decay and pump thermal power contributions, the total thermal power and the corresponding rate of coolant temperature rise in the absence of a heat sink are tabulated below for time zero, 1 minute, and 8 hours after a reactor trip. These high rates of coolant temperature rise show the crucial importance of maintaining cooling after

| Time after Shutdown | 0 | 1 Minute | 8 Hours |
|---|---|---|---|
| Fission Power (MW(th)) | 2238 | negligible | negligible |
| Fission Product Power (MW(th)) | 143 | 96 | 24 |
| Pump Power (MW(th)) | 21 | 21 | 21 |
| Total Thermal Power (MW(th)) | 2392 | 117 | 45 |
| Rate of Coolant Temperature Rise on Loss of Heat Sink, Assuming Initial Coolant Temperature About 250°C (°C/minute) | | 5 | 2 |

shutdown. (Note that coolant temperature would rise at these rates only until boiling occurred, but that boiling would eventually result in core damage.)

## II. HEAT TRANSFER PATHS FOR VARIOUS OPERATING CONDITIONS

This section discusses heat transfer paths from the fuel, via various intermediate heat sinks to the ultimate heat sink, for six different reactor operating conditions - some normal and some abnormal. While the list of these six operating conditions is by no means exhaustive, it does nevertheless illustrate the heat transfer process under a wide variety of circumstances. The main heat transfer paths in each case will be shown pictorially as follows:



Please note that the analysis in this section ignores many minor heat transfer paths such as pump jacket cooling, generator stator cooling, turbine lube oil cooling, etc.

(i) Normal Full Power Operation (Figure 4)

Figure 4 shows the various heat transfer paths for normal full power operation. The main path will be discussed first.

Fission, decay and pump heat is transported by the coolant to the boiler* in the Primary Heat Transport loop. Steam transports the heat from the boiler to the turbine. The turbine converts about 30% of the steam's thermal energy into shaft mechanical energy, which is transmitted to the generator via shaft torque. The generator converts this mechanical energy to electrical energy for the grid. The remaining 70% of the steam's thermal energy (65% reactor thermal power) is carried by the steam through the turbine to the condenser, where it is transferred to the condenser circulating water, and thence to the lake**.

The operation of the various other heat transfer paths in Figure 4 is self evident. Note that about 5% of reactor thermal power goes to the lake via the moderator, about 0.3% via the bleed cooler, about 0.4% via the end shield cooling system, about 0.2% via the biological shield cooling system (Pickering NGS-A) and about 0.2% via the reactor vault air cooling units. These heat transfer paths will not be shown on succeeding diagrams, although the reader may assume they are still available for heat removal unless the text states specifically that they are not.

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* Strictly speaking, it is not the boiler itself but the feedwater in the boiler which is the heat sink. Similarly the main condenser is not the heat sink, but rather the condenser circulating water in the condenser, etc. The reader should bear this in mind while studying Figures 4 to 9.

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** Note that the CCW transports the heat from the condenser to the lake but the CCW pumps must be operating to circulate the CCW, or else the heat transport mechanism fails. Similarly the heat transport mechanisms labelled "moderator", "RCW" and "SW" in Figures 4 to 9 take for granted the operation of the respective pumps. The mechanism for circulating the main coolant, however, varies with the reactor operating state, and is specified right on the respective Figures.

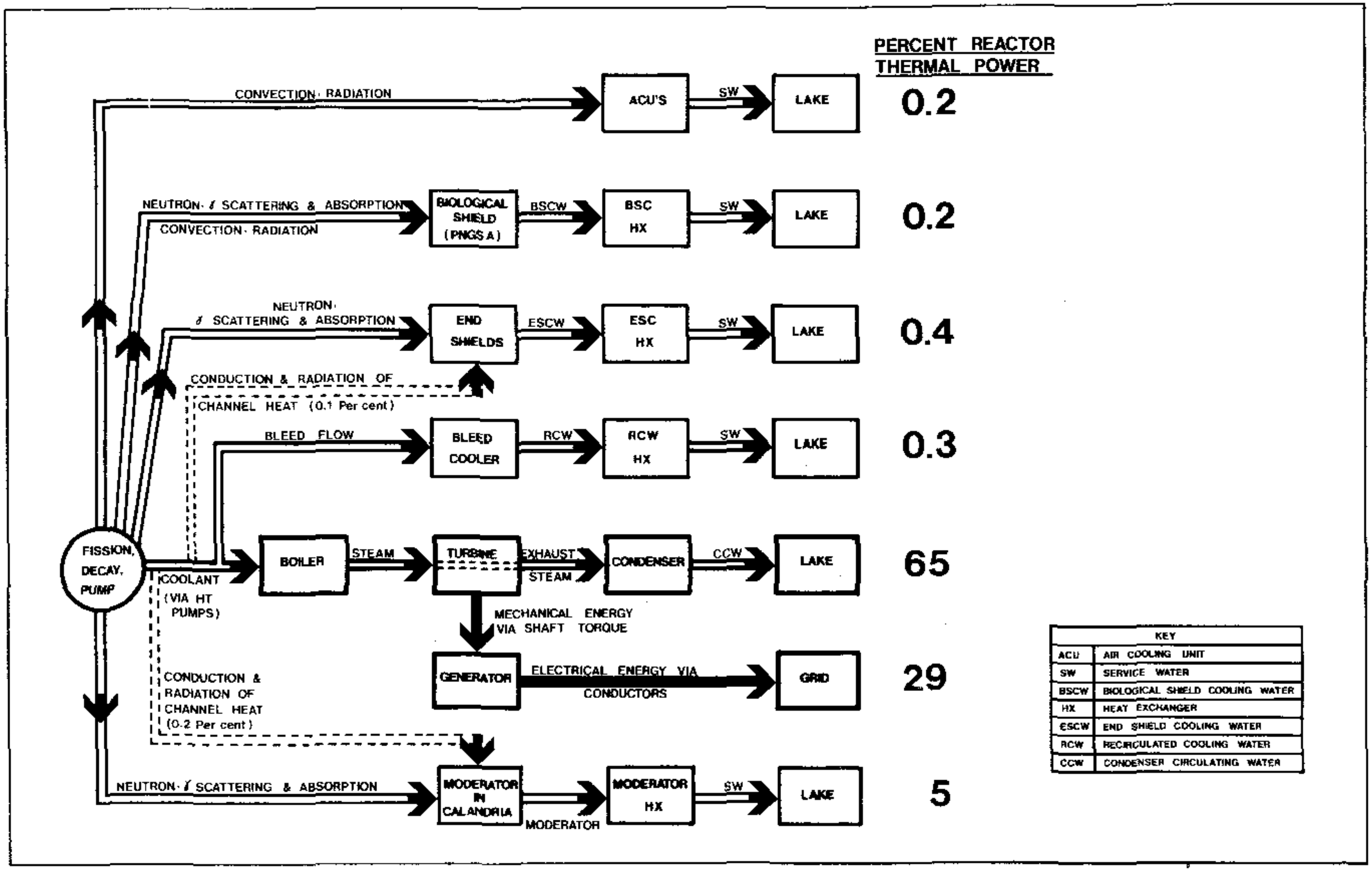


Figure 4: Heat Transfer During Normal Full Power Operation.

(ii) Poison Prevent Mode (Figure 5)

This mode is used to prevent the reactor from poisoning out when steam flow to the turbine is lost with the reactor at power, eg, on a turbine trip, generator trip, or load rejection, and the prospects are good for returning the turbogenerator to service within a few hours. Clearly, the steam must then be discharged elsewhere in order to keep the boiler heat input from the coolant equal to the heat output via the steam. At Pickering, the steam is discharged to atmosphere via steam reject valves (SRV's); at Bruce, the steam is discharged directly to the condenser via condenser steam discharge valves (CSDV's). Although both the SRV's and CSDV's are rated for 100% full power, nevertheless reactor power, and hence steam power, is reduced to the minimum - about 60% to 70% - at which the Xe transient can be overridden. The reasons for reducing power are as follows:

(a) at Pickering, to conserve feedwater, which is being lost to the atmosphere.

(b) at Bruce, to avoid overloading the condenser.

Figure 5(a) depicts the Poison Prevent heat transfer chain for Pickering. The coolant transports fuel and pump heat to the boiler, and steam transports the heat from the boiler to the atmosphere via the SRV's.

Figure 5(b) depicts the corresponding process at Bruce. Steam transports the heat from the boiler to the condenser via the CSDV's, and the CCW transports the heat from the condenser to the lake.

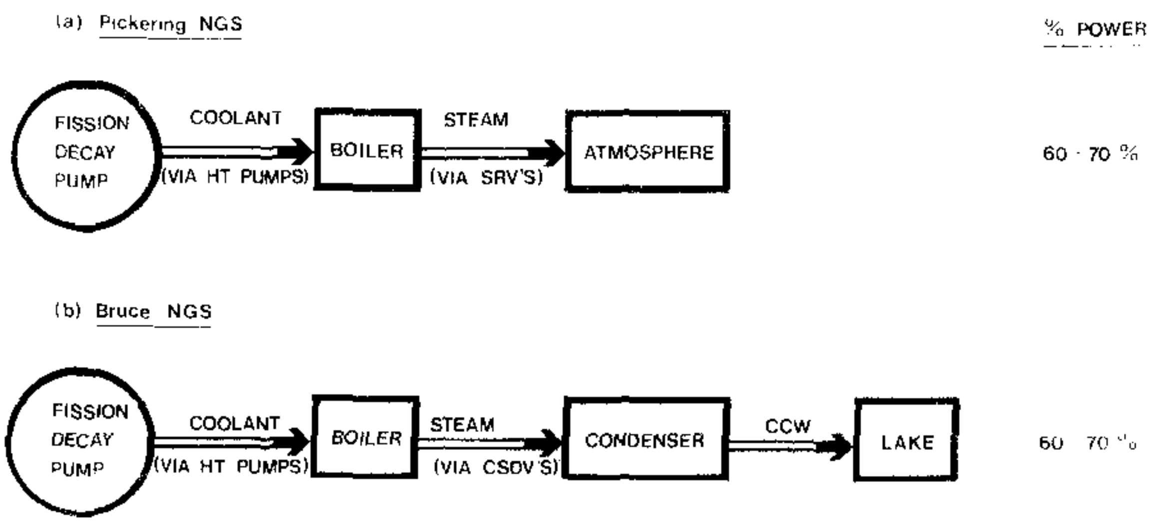


Figure 5: Poison Prevent Mode.

(iii) Operation of Boiler Safety Valves (Figure 6)

Should, for any reason, boiler steam flow become inadequate to match coolant heat input to the boiler, then boiler pressure would rise until the safety valves blew. Figure 6 illustrates the heat transfer path opened up by the safety valves: reactor and pump heat is transported by the coolant to the boiler, and thence by steam to the atmosphere via the safety valves. Note that the path of Figure 6 will be supplementing other paths through the turbine and/or the steam discharge valves (SRV's or CSDV's), unless both of these latter paths were lost simultaneously with the reactor at power.

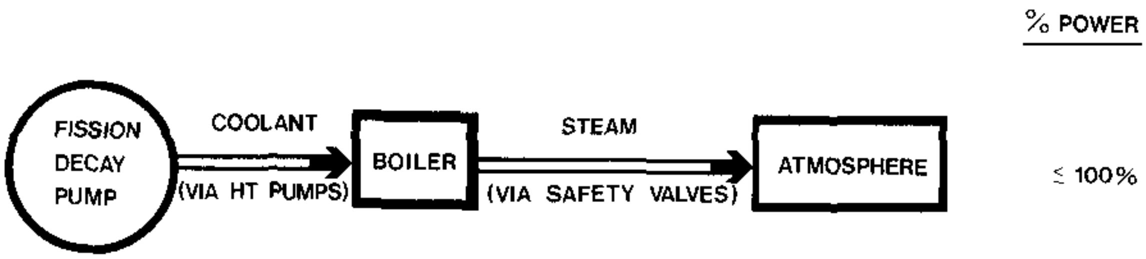


Figure 6: Operation of Boiler Safety Valves.

(iv) Shutdown Cooling in Service (Figure 7)

This mode of operation is discussed in lesson 233.30-5. Figure 7(a) shows the Shutdown Cooling (SDC) heat transfer path at Pickering, where the main heat transport pumps are shutdown in this mode. Decay heat (SDC pump heat is negligible by comparision) is transported by the coolant to the SDC heat exchanger, and thence, via service water, to the lake.

Figure 7(b) (i) depicts the corresponding process at Bruce, where the main heat transport pumps operate in the SDC mode. Here decay and pump heat are transported via the coolant to the preheater, thence via feedwater in the SDC loop to the SDC heat exchanger, and thence via service water to the lake.

Figure 7 (b) (ii) shows the heat transfer path with the Bruce Maintenance Cooling System (MCS) in service (see lesson 233.30-6). The main heat transport pumps are shut down in this mode. Decay heat is transported via the coolant to the MCS heat exchanger, and thence via service water to the lake.

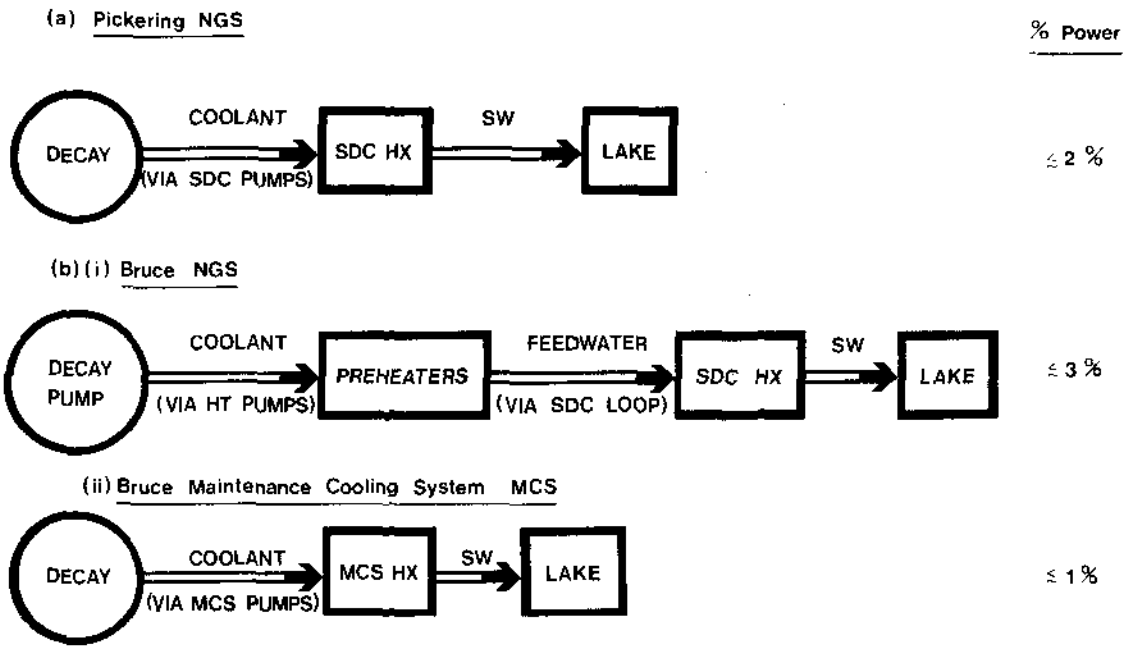


Figure 7: Shutdown Cooling In Service.

(v) Loss of Class IV Power (Figure 8)

On a loss of Class IV power, the main heat transport pumps and also the main boiler feedwater and CCW pumps would be unavailable. The reactor trips on loss of Class IV power (on low heat transport flow and/or high heat transport pressure), and fission power starts to decay according to Figure 2.

(a) Pump Flywheel Rundown

Figure 8(a) shows the heat transport chain during the first 2 to 3 minutes following a loss of class IV power, while the pumps are slowing down gradually due to flywheel inertia. During this interval, fission, decay and residual pump heat is transported by the coolant under forced circulation to the boiler, and thence via steam to the atmosphere via SRV's (Pickering) or ASDV's (Bruce).

(b) Thermosyphoning

Figure 8(b) shows the heat transfer process following flywheel rundown, when heat is transported via the coolant to the boiler by the process of natural convection alone. Hot water rises from the core to the physically highest point in the HT loop, ie, the boilers, where it is cooled. The cooler, denser $D_2O$ then 'sinks' back down to the reactor, completing a natural convection loop. Without boiler feedwater, which is the vital heat sink for the process, the transport mechanism of thermosyphoning will not work, as natural circulation flow could not then be established.

Incidentally, since the main feedwater pumps are also lost on a Class IV outage, feedwater will be supplied to the boilers by the auxiliary feedwater pump, which is rated for about 3% full feedwater flow and supplied by Class III power.

The auxiliary feedwater supply is backed up by the emergency feedwater supply from storage tanks (Pickering), or by low pressure water from the fire protection system or from the CCW duct via diesel operated pumps (Bruce). These backup supplies are also rated for 3% full feedwater flow. In case of total failure of feedwater supply, there is still a holdup of feedwater in the boilers amounting to about 1.5 full power minutes' supply.

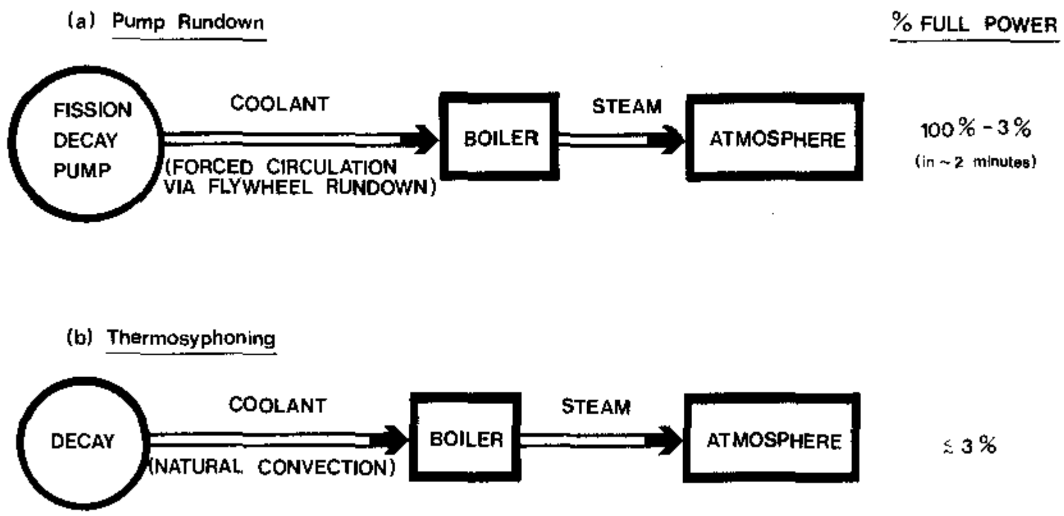


Figure 8: Loss of Class IV Power.

(vi) Loss of Coolant Accident (Figure 9)

(a) Emergency Core Injection System (ECIS) in Service

The ECIS is discussed in section 233.30-11. By the time the recirculation phase of injection is reached, the decay heat is less than about 3% full power. Figure 9(a) shows that this heat is transported by the injection water, including whatever remains of the original coolant, to the ECI heat exchangers, and thence via service water to the lake.

(b) ECIS Unavailable

Heat removal via Air Cooling Units (ACU's), Biological Shield Cooling (BSC), End Shield Cooling (ESC), and the Moderator Circulating System during normal operation is something of a necessary evil, since it represents a loss of heat to the electrical generation process. However, in the context of the extremely unlikely "dual failure" of heat transport boundary and ECIS, such heat transfer paths become critically important for removing decay heat.

As long as any water remains in the Heat Transport System, fuel heat will be removed by boiling water to steam. The ACU's can remove up to 1% full power by condensing steam. Excess steam might condense on other equipment and structures or be swept into the vacuum building.

Once the HTS is empty, heat transfer is possible only by conduction, convection and thermal radiation to the ESCS, ACU's, BSCS and through the annulus gas to the moderator. About 0.3% full power, corresponding to decay heat about 10 days after shutdown, is removable by such paths. If decay heat were greater than 0.3%, the fuel would heat up until the pressure tubes sagged into the calandria tubes, at which point heat transfer to the moderator would improve substantially. Further damage would then be unlikely, provided moderator circulation could be maintained.

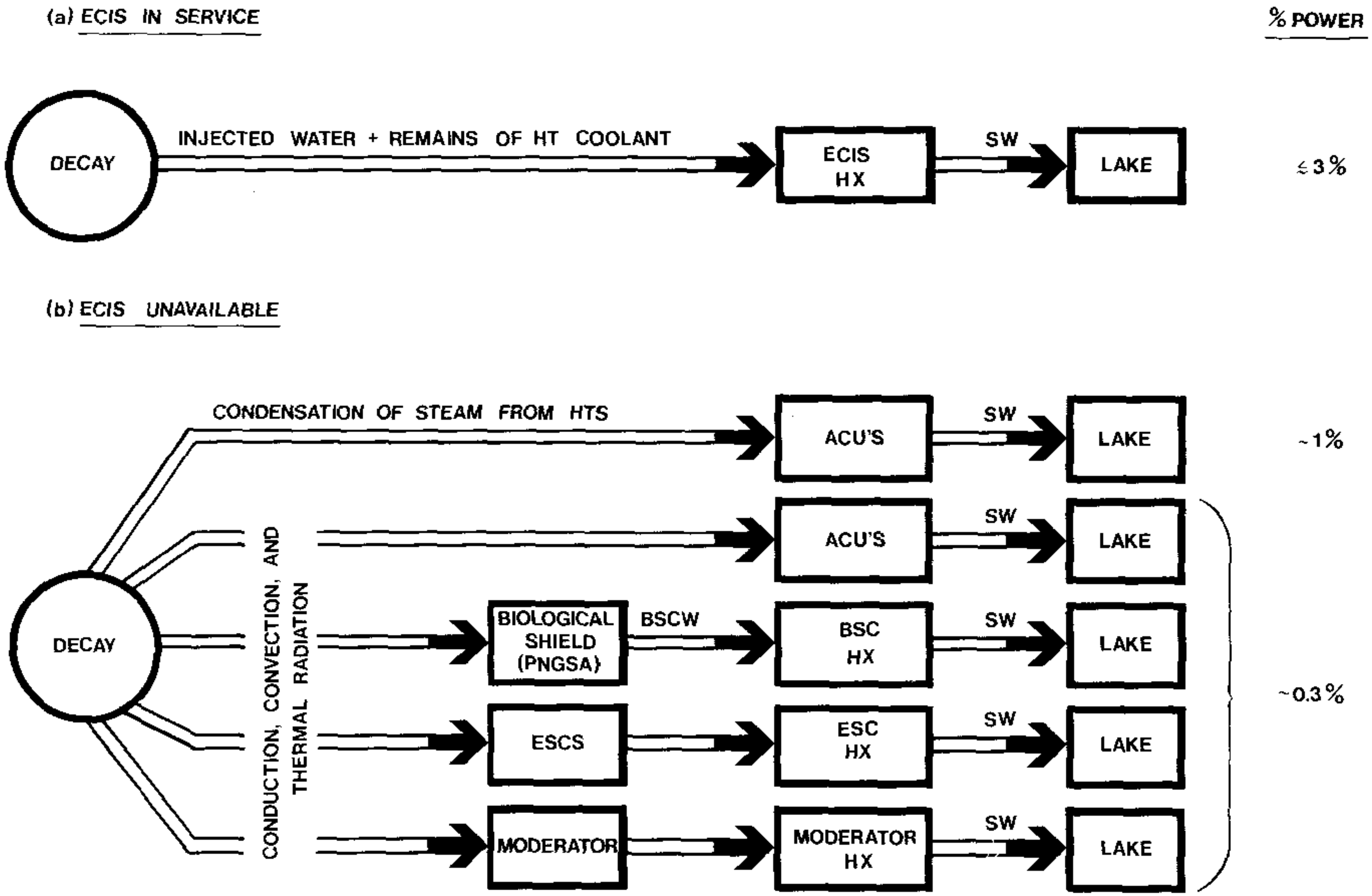


Figure 9: Loss of Coolant Accident.

## ASSIGNMENT

1. State two heat sinks available to remove 100% reactor thermal power.

2. Assuming the reactor just shut down and HT pumps not available due to loss of Class IV power, state two heat sinks available to remove decay heat.

3. The text states that CANDU boilers have approximately 1.5 full power minutes of feedwater holdup. Approximatey how many minutes of feedwater holdup inventory will there be if the reactor is tripped at full power with normal boiler level? Use Figure 6 plotted on linear time and power scales to estimate your answer. This number indicates how much time is available to restore feedwater in the event of a complete cut-off of feedwater flow, or to establish an alternate heat sink on a reactor trip.

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