Intermediate Reactors and Auxiliaries

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1 Objectives

1.1 Introduction

This course begins with a review of the basic purposes and operation of a CANDU reactor, covered in *CANDU Fundamentals*. The moderator and heat transport systems, along with their major auxiliaries are studied in greater depth of detail than in *CANDU Fundamentals*. Other systems included in this course are the special safety systems, annulus gas, and end shield cooling. In addition, you will learn about operational concerns and abnormal events.

1.2 Moderator

1.2.1 Moderator heavy water

- Identify one indication available to alert the control room operator to a low isotopic.

- State the consequences of sudden (acute) downgrading of the moderator isotopic.

- State the primary radiological hazards from the moderator during operation and shutdown.

- Describe two ways the moderator system is used to guarantee the reactor shutdown.

1.2.2 Moderator Circulation System

- Explain the possible consequences of operating with the moderator temperature too high.

- Under normal operating conditions, state the required level of moderator D_2O

- Describe the adverse consequences of operating outside this level for your station.

- Briefly explain the adverse consequences of the following abnormal conditions: loss of service water to the moderator HXs, loss of moderator circulation flow, moderator heat exchanger leak

1.2.3 Cover Gas System Circulation & Pressure Control

- State the lower explosive limits of D_2 and O_2 in a helium atmosphere.

- State six factors that affect the concentration of D_2 and O_2 in the cover gas and explain how each affects the gas concentrations.

- List the operating states that require cover gas circulation and explain three reasons for this circulation requirement.

- Explain the three conditions that require cover gas purging.

- Explain the required precaution while purging the cover gas.

- State the two methods that are used to ensure that D_2, O_2 and N_2 concentrations in the cover gas are within the allowable limits.

- Explain the possible significant consequence and general methods to minimize or offset the consequences for each of the following abnormal concentrations of D_2 and N_2 in the moderator cover gas:

- Explain two methods used to determine if a cover gas recombination unit is operating.

1.2.4 Moderator Liquid Poison System

- For various operating states explain why poison might be added to the moderator, which poison might be used and why that poison is chosen.

- If poison addition is done manually, list four general indications used to monitor/control poison addition is taking place.

- State the source of information used to ensure that the correct amount of poison has been added to the moderator:

- State the reason why there is an automatic Gd addition feature.

- State the indicated number of unit responses/concerns, or indications during specified abnormal circumstance. :

1.2.5 Moderator Purification System

- State three reasons why it is important to maintain moderator purity.

- State three ways in which moderator purity is controlled.

- Describe the term purification half-life.

- State the primary control for the rate of gadolinium poison removal.

- Explain the reason why a multistage ion exchange technique is required for boron removal.

- State three reasons why boron or gadolinium should be removed when their reactivity effects are no longer required.

- State how moderator purification parameters are maintained: purification flow, ion exchange inlet temperature, purification pressure, conductivity.

- Explain the significant operating consequences abnormal circumstances in the moderator purification system.

- State the reason why the moderator purification system must be isolated during unit overpoison guaranteed shutdown state.

1.3 Heat Transport System

1.3.1 HTS Heat Sources & Heat Transfer Paths

- Describe the heat transfer paths during normal and poison-prevent operation.

- State and explain the general constraints on HT system operation for the prevention of Delayed Hydride Cracking (DHC).

- Explain the two major potential hazards associated with the HT system.

- State two hazards associated with hydrogen added to the HTS.

1.3.2 HTS Pressure & Inventory Control

- Explain the reasons why the HTS pressure must be maintained between upper and lower limits.

- Explain two concerns with blocked or restricted coolant paths.

- State the three effects of boiling in the HTS and,

- State when boiling in the HTS is permissible at some stations.

- Explain why it is necessary to have HT system pressure/inventory control.

- State four purposes of the feed and bleed system for units with a pressurizer while in solid mode pressure control.
- State the purpose of the pressurizer during normal heat transport operational mode.
- Explain how a pressurizer maintains HT system pressure to a predetermined set point.
- State five purposes of the feed and bleed system for units with a pressurizer while in normal mode pressure control.
- State five purposes of the feed and bleed system for units without a pressurizer.
- Give three reasons why the pressurizer level is controlled.
- Explain how shrink and swell are made up between cold pressurized and zero power hot in units with no pressurizer.
- Explain two major purposes of the inter-unit D_2O transfer system.
- Explain the three major purposes of the HT D_2O storage tank.
- Explain two reasons that a lower operating limit is placed on the D_2O storage tank level.
- Explain two reasons that an upper operating limit is placed on the D_2O storage tank level.
- Explain how pressure is control is achieved in a bleed condenser.
- Explain how pressure is controlled in a degasser condenser.
- For both types of HT system (pressurizer and no pressurizer) state the response during slow power maneuvers, of specified parameters. HTS pressure, HTS average temperature, Feed and bleed flows, Pressurizer level, Boiler pressure.
- State why it is necessary to have HTS pressure relief.
- Explain the two major causes of HTS over-pressurization.
- Define the terms direct pressure reduction and indirect pressure reduction.

- Explain how direct pressure reduction is accomplished.

- Explain how indirect pressure reduction is accomplished.

- Describe the major effects of various process upsets: Failed open Pressure Relief Valve, feed pump failure, steam bleed valve fails open, failure of a main HTS pump

1.3.3 Heat Transport System Shutdown Operation

- Explain the operation of the two types of shutdown cooling systems used in CANDU reactors, ie, indirect and direct.

- Explain the reason for the class of power supply provided for the direct and indirect shutdown cooling systems.

- Explain how thermosyphoning is achieved in a CANDU reactor.

- State four conditions required to maintain thermosyphoning.

- Define the term crash cooldown.

- Explain the constraints on using shutdown-cooling systems for emergency cooldowns.

1.3.4 HTS Heavy Water

- Explain, two reasons, why the heat transport system heavy water has a minimum isotopic limit.

- Explain why there is an upper isotopic limit for the heat transport system heavy water.

- State four major causes of HTS downgrading.

- State the immediate and long term effects of the HT coolants sudden downgrading.

- State four potential radiological hazards of heat transport D_2O when the reactor is shut down.

- State two additional potential radiological hazards of heat transport D_2O when the reactor is operating.

- Explain the major purpose(s) of each of the specified collection systems: heat transport D_2O collection system (1), miscellaneous

D_2O collection system (1), vapour recovery system (4), liquid D_2O recovery system (1)

- State three reasons why there are limits on isotopic and purity of D_2O for return to the heat transport system.

- State the possible significant consequences of abnormal conditions: an abnormally high D_2O recovery/collection rate (over a period of time) (3), A pressure tube leak (1), A boiler tube leak (2).

1.3.5 Heat Transport System Auxiliaries

Purification

- Explain 3 reasons why the heat transport purification system inlet temperature is important.

- Describe how purification inlet temperature is maintained for purification systems operating at reduced pressures,

- Describe how purification inlet temperature is maintained for purification systems operating at full HTS pressure.

- Explain 2 reasons why the heat transport purification system flow is important, and describe how it is maintained for:

- Describe how purification flow is maintained for purification systems operating at reduced pressures,

- Describe how purification flow is maintained for purification systems operating at full HTS pressure.

- Explain why the ΔP across the heat transport purification system IX column is important.

- Explain 3 reasons why the heat transport purification system inlet pressure is important.

- Describe two methods of preventing excessive pressures.

- State two heat transport system conditions that require an increase in the rate of removal of heat transport impurities.

- Describe how this increased removal rate is achieved.

Hydrogen Addition

- Explain the purpose of hydrogen addition to the heat transport system.

- Explain the major concern associated with H2 concentration in the HTS out of limits.

- Explain the consequences of H_2, D_2, and O_2 coming out of solution.

Gland Seal Supply

- State the two major purposes of the gland seal supply system.

- Explain why D_2O supplied for gland sealing must be filtered, pressurized and cooled.

- State where the back-up gland sealing supply comes from.

- State four parameters that are monitored to verify seal problems.

1.4 Special Safety Systems

1.4.1 Shutdown Systems

- State the two generic abnormal conditions against which the shutdown systems are designed to protect CANDU units.

- Explain the requirement for a shutdown system.

- Describe thee types of CANDU shutdown systems

- Explain why shutdown systems must be independent of each other and of all process systems.

- Explain why a shutdown system should be a fail-safe system.

- Explain the reason why safety interlocks are tied into the shutdown system.

- Explain the difference between an absolute and conditional trip.

- For specified situations explain which absolute trip parameter is commonly provided to protect the unit: loss of regulation, loss of primary heat sink.

- Explain the importance of redundant parameters for shutdown system actuation.
- State two reasons for providing the capability to actuate SDS1 and SDS2 manually.

1.4.2 Emergency Coolant Injection

- State the purpose of the Emergency Coolant Injection System (ECIS).
- State what is meant by a Loss of Coolant Accident (LOCA).
- State the key parameter that will cause a reactor trip for small and large LOCA's
- State the parameters that must be satisfied before ECIS will be initiated.
- State the other safety systems which may be activated following a LOCA.
- Explain the three operational phases of ECI
- Explain giving the three reasons why ECIS initiates a crash cooldown.
- Explain two reasons for operating HT pumps for as long as possible following a LOCA.
- Describe the sequence of operation of the major components and their function in the operation of ECIS:
- Define terms related with the operational state of ECI: poised, blocked, recallable.
- State the two major consequences or concerns associated with a failure to block ECIS before depressurization of the heat transport system.
- List the required reactor state when the ECIS is blocked.
- State two reasons why ECI can be initiated manually.

1.4.3 Containment

- State the two types of containment systems in use with CANDU reactors and identify the poised system common to both types.
- State how pressure is normally maintained subatmospheric for a Pressure Suppression Containment system.
- State two functions that the total water inventory in containment must provide in the event of a LOCA.
- Describe the functions of a pressure suppression containment (PSC) system and how dousing is initiated.
- Describe the function of the vault coolers
- Describe containment box-up or button-up
- Describe the operation of containment systems
- State the purpose of airlocks for both types of containment systems.
- Explain the purpose of the Filtered Air Discharge System (FADS).
- Explain the purpose of the hydrogen igniters
- State how pressure is normally maintained subatmospheric in containment.
- Explain the availability requirements of containment.

1.5 Reactor Systems

1.5.1 Annulus Gas System

- State three important benefits obtained by using CO_2 as the annulus gas.
- State the reason why the annulus gas system must be circulating in order to fulfill its purposes.
- Explain why annulus gas parameters is monitored, and give a typical normal operating range of values: pressure, dew Point
- List six reasons why purging of the annulus gas system may be required.

- For given abnormal conditions, state the indicated number of major operating concerns.

- State when the annulus gas system may be stagnant.

1.5.2 Shield Cooling Systems

- State the reason why the end shield requires cooling.

- Explain the consequence of the loss of end shield cooling.

- State the approximate percentage of reactor thermal power removed by the end shield cooling system.

- Describe the heat removal path of the shield cooling system

- Explain why the end shield cooling system purification loop is required.

- Explain three parameters, other than the controlled variable (temperature), which must be monitored to ensure that end shield cooling system performance is adequate.

- State three required actions when end shield cooling has been lost.

- Explain three conditions that must be satisfied to allow the end shield cooling system to be taken out of service.

- Explain the three special precautions required if the end shield is to be drained.

- State the reason why the biological/thermal shield requires cooling.

- Explain the consequences of the loss of biological/thermal shield cooling flow.

- State the approximate percentage of reactor thermal power removed by the biological shield cooling system.

1.6 Fuel

1.6.1 Fuel Performance

- List seven factors that contribute to fuel failures during reactor operation.

- List the methods that can be used to minimize each of these factors.
- Explain two factors that can cause high fuel temperatures.
- Describe the effect on flux shape of replacing high burnup fuel with fresh fuel while operating at power.
- Explain how shutdown fuelling could lead to an unacceptable spatial flux distribution on restart.
- Describe what the term Reference Flux Shape means
- Explain why the flux shape in an operating CANDU differs from the reference shape.
- Define the following terms as they apply on an operating CANDU reactor: fuelling ripple, channel power peaking factor (CPPF).
- State why bulk power is limited when the reactor is operating with adjusters out of core.
- State how the reactor is protected from excessive high power when operating in an unanalyzed flux shape.
- Explain the reason for a limit on the amount of power to be extracted from a fuel bundle or channel, and the consequence of exceeding these limits.
- State the information typically available to the operator to ensure that the bundle power limit is not exceeded by any bundle
- State three reasons for detecting, locating, and removing failed fuel from the reactor.
- Explain of general techniques used for detecting and locating failed fuel.
- State three methods that can be used to reduce iodine concentrations in the coolant, assuming the concentration is rising from just below the action limits to shutdown levels.
- Explain why high iodine concentrations may occur on a shutdown even though the shutdown process itself did not cause fuel to fail.

1.6.2 Fuel Handling

- Explain the factors is used to determine if a channel can be fuelled: channel burn-up, power distribution, reactivity gain, channel abnormal conditions, defective fuel in the core, proximity to recently fuelled channels, abnormal operating conditions, liquid zone levels

- Explain three reasons, the preferred reactor state during refueling.

- Explain three methods that are used in CANDU reactors to detect flow blockages while fuelling.

- Explain three major concerns when handling irradiated fuel.

- Explain the additional precaution taken when handling failed fuel.

- Explain the reasons for monitoring four parameters in the water of the irradiated fuel bay.

- Explain the parameter monitored in the irradiated fuel bay atmosphere.

2 Moderator

2.1 Moderator heavy water

In this section of the course we will discuss some characteristics of the moderator heavy water, moderator isotopic, moderator radiological concerns, reactor shutdown guarantee

2.1.1 Moderator Isotopic

Isotopic Calculation

Isotopic of heavy water is the standard way of describing the concentration of heavy water. Isotopic is defined as the mass of D_2O divided by the total mass of D_2O and H_2O in a given sample. For instance, if in a sample of 20g we have 19.6 g of D_2O and 0.4 g of H_2O, the isotopic content will be:

$$\frac{19.60}{19.60 + 0.40} \text{ x } 100 = \frac{19.60}{20} \text{ x } 100 = 98\%$$

Acceptable Range

High moderator isotopic is required so that the moderator can fulfill its prime function of slowing down fission (fast) neutrons efficiently with a minimum of absorption, i.e., be an effective moderator. The minimum acceptable specification is ≥ 99.8%. Moderator isotopic within this range will provide sufficient reactivity to achieve reasonable fuel burnup. The isotopic strongly affects reactivity and hence fuel costs. Higher isotopic means a smaller number of parasitically absorbed neutrons (see Table 2.1 for a 540 MWe unit).

Table 2.1

Change in D_2O Isotopic	+/- 0.1%
Δk Change	+/- 3.6 mk

A lower fueling rate is required at a higher isotopic. The lower the fueling rate, the higher the fuel burnup, i.e., $MWh_{(th)}$ produced per kg uranium. Most multi-unit stations have upgraders so that the isotopic can be continuously upgraded. Typically, these stations are operating at about 99.9% isotopic.

Isotopic Limit

If the moderator isotopic is too low, the overall core reactivity will be too low. Let us suppose that the moderator isotopic went from 99.80% to 99.45%. From Table 2.1, the core reactivity change would be 12.6 mk. This is an enormous amount of reactivity, which cannot be compensated for by the zone levels. An economic penalty will occur to maintain the reactor critical. To accommodate this large reactivity change and maintain the reactor critical, two methods may be used: withdrawal of adjuster rods, increased fuelling.

Withdrawal of adjuster rods (where available)

During normal operation, the adjuster rods are fully in core. Removing these neutron absorbers from the core will increase core reactivity (but will probably require derating to keep within analyzed flux shapes).

Increased fuelling

Additional new fuel is added to the core to increase core reactivity. This is associated with a fuel burnup penalty, since fuel is removed before optimum burnup.

The main indication available to alert the operator to an acute reduction in moderator isotopic is the average zone level decreasing to compensate for the reactivity loss. When the zones reach their lower limit the withdrawal of adjuster rods will be required. All stations after Pickering ‘A’ have automatic protective actions initiated on regional over power.

A slow or chronic lowering of isotopic would normally be detected via routine lab analysis.

There is no upper limit on the moderator isotopic as far as reactor operation is concerned. The isotopic is increased by makeup of higher isotopic moderator D_2O from the moderator upgrader.

Downgrading

Downgrading during normal operation may occur by accidental addition of H_2O or D_2O downgraded below system isotopic. Equipment failure such as moderator heat exchangers, end shield cooling, or liquid zone leaks could also contribute to downgrading. H_2O vapour may ingress via moderator D_2O collection system tank returns. The effects on normal reactor full power operation are identified in the following chart.

Table 2.2

Effects of downgrading Moderator D_2O

Change in moderator isotopic from reference operating value 99.8%	Short term effect	Long term effect
Isotopic slowly increasing from high isotopic moderator makeup	No observable effect, isotopic change too small	Fuelling rate reduced slightly. Higher average fuel burnup.
Downgrading of less than or equal to 0.3%	Operation continues with a drop in average liquid zone level, (adjusters may be required to move out)	Increased fuelling rate needed to return (and maintain) zone levels/adjusters to normal operating positions. Lower average fuel burnup.
Acute downgrading greater than 0.3%	Shutdown, if Δk from zones/adjusters is inadequate to maintain criticality.	Lengthy shutdown until new or upgraded D_2O is supplied.

2.1.2 Moderator Radiological Concerns

The design of the moderator system has attempted to reduce the radiological concerns in various ways.

The moderator equipment such as pumps, heat exchangers and piping are located in shielded and access-controlled areas, mainly because of high gamma fields from N^{16} and O^{19}. The access-controlled areas are not accessible while operating at normal reactor power because of the radiological hazard. The piping is designed to minimize potential leak sources and eliminate pockets and strainers where activated material can build up. All materials used for equipment are low cobalt content.

Two major radiological concerns associated with the moderator system will be discussed in detail: gamma radiation from N^{16} and O^{19}, beta radiation from ${}_1H^3$

Figure 2.1 gives an indication of on power radiation field buildup from N^{16} and O^{19} gamma radiation. When operating, the high fields peak at about 10 R/h. After shutdown, the short-lived radioactive daughters decay away within one minute from shutdown.

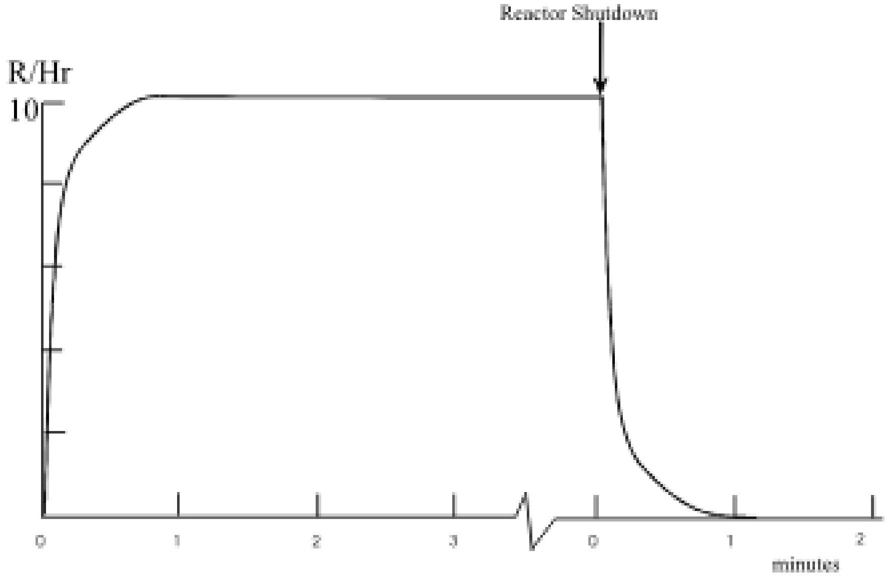


Figure 2.1
Gamma Radiation Fields Due to N^{16} & O^{19}

Tritium buildup (Ci/kg) in the moderator is also a major radiological concern. It builds up more quickly in the moderator than in the heat transport system, the three reasons for this are explained below.

1. Thermal neutron flux is about twice as high in the moderator as in the heat transport system within the core. This is because the

moderator is the source of thermal neutrons while the fuel is a sink (HT fluid in the vicinity of the fuel has a flux depression for thermal neutrons).

2. The majority of the moderator D_2O spends a longer time in the core than HT D_2O. Hence the moderator D_2O absorbs more thermal neutrons giving a higher tritium concentration.

3. HTS is a more complex system, leading to higher leak rates than moderator system. Make-up to the HTS dilutes the $_1H^3$ concentration more than in the moderator.

When moderator D_2O escapes from the system, tritium concentration becomes a radiological concern. Because the half-life for tritium is about 12 years, the concentration builds up slowly to an equilibrium level. In practice, this concentration is reduced because of:

a) Outages and operation at lower than maximum reactor power;

b) Low tritium concentration makeup D_2O to the moderator.

Prior to tritium reduction programs made possible by the Darlington tritium removal facility (TRF), equilibrium concentrations in mature stations ranged typically from 20 - 40 Ci/kg D_2O. Currently concentrations of $\approx$10 Ci/kg D_2O are being achieved.

The following three conditions are hazards associated with the operation of the moderator system.

2.1.3 Moderator D_2O spilled during shutdown

When moderator D_2O escapes from the reactor or is spilled during shutdown, the following primary radiological hazards exist:

- Tritium
- Activation products, dissolved as ionic impurities and/or entrained insoluble products

When shut down, the short-lived isotopes, N^{16}, O^{19} decay quickly. Photoneutrons will contribute to the fields for about the same length of time.

2.1.4 Moderator D_2O spilled on power

When moderator D_2O escapes from the reactor or is spilled during normal power operation, the following primary radiological hazards exist:

- Gamma radiation (N^{16}, O^{19}) from moderator core and piping (for a few seconds)
- Tritium
- Activation products, dissolved as ionic impurities and/or entrained insoluble products
- Beta radiation hazard at the hole in the piping system
- Photoneutrons from N^{16} (for a few seconds)

2.1.5 Moderator D_2O Contained In Pipework On Power

The main radiological concerns associated with moderator D_2O sealed in the moderator circuit on power include the following.

- Gamma radiation (N^{16}, O^{19});
- Gamma radiation from activation products - soluble or insoluble;
- Photoneutrons from N^{16}.

When the reactor is shut down, the gamma radiation from N^{16} and O^{19} will be essentially zero. Activation product radiation will be the only primary concern.

As long as the moderator is contained in the circuit, tritium is of no concern, because its beta radiation cannot penetrate the pipework. However, in practice, moderator auxiliary rooms have tritium vapourized as an airborne emission, from leaks. Systems are in place to recover D_2O vapour as a liquid. This is done to reduce tritium exposure as well as to recover D_2O for economic reasons.

2.1.6 Reactor Shutdown Guarantee

There are two ways the moderator system is used to guarantee that the reactor is shut down:

Moderator Poisoning

This method places the reactor in a guaranteed shutdown state due to the very high insertion of negative reactivity. Typically, moderator poisoning inserts hundreds of mk of negative reactivity. A flowpath in the moderator system is set up to ensure: (i) poison is not removed by purification; (ii) poison is not diluted by unpoisoned water; (iii) and poison is not drained out. The moderator D_2O must also be continuously circulated and monitored by sampling for poison concentration and pH usually twice per shift to ensure the guarantee. If the pH is not correct the poison can precipitate out of solution.

Moderator Draining

It is not possible for a natural uranium reactor to achieve criticality without the moderating effect of the D_2O in the calandria. In this case a hole is guaranteed in the calandria by guaranteeing certain drain valves open. This prevents moderator D_2O from inadvertently accumulating in the calandria. Pickering 'A' uses a moderator dump as a shutdown system.

2.1.7 Summary Of The Key Concepts

- Concentration of heavy water is expressed as a percentage weight of D_2O in a given sample, called isotopic.
- The normal range of isotopic is ≥ 99.8
- A low limit on isotopic is imposed to minimize the economic penalty, and to ensure the reactor maintains critical.
- The average zone level will decrease as a result of low isotopic.
- Sudden downgrading of the moderator isotopic will cause a drop in the average zone level. The adjusters may be signalled to move depending on the average zone level and power error.
- During shutdown, the radiological hazards from spilled moderator D_2O include tritium, and activation products.
- During normal power operation, radiological hazards from spilled moderator D_2O include:
    - Tritium
    - Gamma radiation from N-16 and O-19
    - Activation products
    - Beta radiation from the leak
    - Photoneutrons from N-16 & D_2O
- During normal power operation, radiological hazards from moderator in the pipework include:

- Gamma radiation from N-16, O-19 and photoneutrons
- Activation products
- The moderator system can guarantee the reactor shutdown by moderator poisoning or by draining the moderator from the core.

2.2 Moderator Circulation System

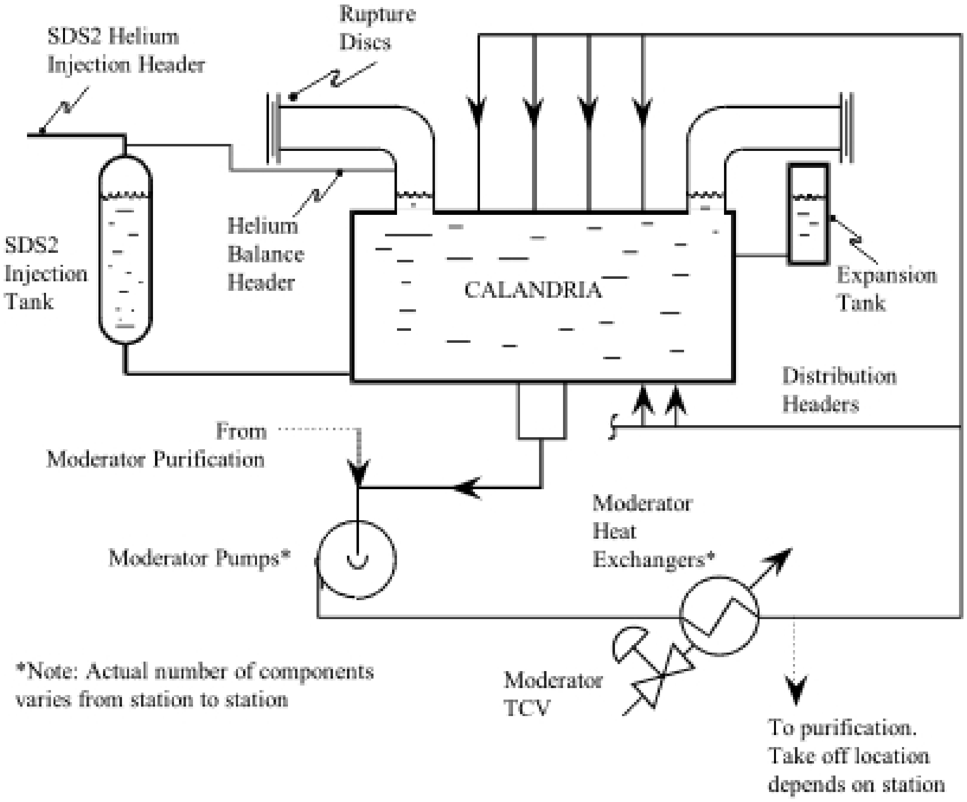


Figure 2.2
Typical Moderator Circulation System

This section of the course will examine the moderator circulation system. We will cover heat sources, heat removal, bulk moderator temperature, consequences of localized hot spots, improper moderator level, loss of moderator cooling and moderator heat exchanger leaks. Ref. Fig. 2.2

2.2.1 Heat Production

In the process of moderating the nuclear reaction, the moderator is subject to considerable heat production. The heat absorbed by the moderator is approximately 5% of the reactor's gross thermal power production.

Thermal energy in the moderator is supplied as a result of the following**:** thermalization of neutrons, absorption of gamma rays and convetional heat transfer.

Thermalization of neutrons

This is a major heat source when the reactor is on power. As neutrons impact with D_2O nuclei, a transfer of kinetic energy from the neutrons to the D_2O occurs. This results in increased energy of the D_2O seen as an increase in temperature.

This source quickly diminishes when the reactor is shut down.

Absorption of γ radiation

Some γ radiation gets absorbed by the D_2O molecules increasing molecular energy and moderator temperature.

The magnitude of heat input rate is highest when the reactor is on power; however, it remains significant for a long time after shutdown.

Conventional heat transfer

Despite the use of CO_2 as the annulus gas, some heat still radiates from the fuel channels to the moderator.

Conduction through the end fitting, bellows, end shield and other structural parts, also results in heat transfer from the fuel to the moderator.

This source of heating is dependant on the difference in temperature between the moderator and the fuel channel, hence, it either remains constant from ZPH to full power, or varies slightly with reactor power depending on the station.

2.2.2 Heat Removal

Heat must be removed from the moderator to prevent an increase in its temperature and the resulting adverse consequences discussed later in this section. Since the moderator is continually picking up heat due to the sources mentioned above, its temperature will increase unless a heat sink of equal capacity is provided.

The moderator is continuously circulated through a heat exchanger by pumps providing the required heat sink. The shell side of the heat exchanger has low pressure service water . The return of the moderator water into the calandria is done through various entry points to minimize the formation of hot spots, ensuring adequate cooling of all components, and helping to distribute poisons.

2.2.3 Moderator Temperature Control

The moderator temperature is controlled by varying the service water flow rate through the moderator heat exchangers. The temperature at the moderator outlet is controlled to 61°C. The outlet temperature is part of the station OP&P. Exceeding the moderator outlet temperature must be prevented for the following reasons: accident mitigation, reactivity effects, explosion hazard, metallurgy considerations.

Accident Mitigation

The moderator may have to act as a fuel heat sink in the event of a LOCA combined with coincident failure of ECI. In this situation, fuel channel voiding will cause fuel channel overheating. And, if fuel cooling is not restored, the fuel channels will sag, eventually contacting the calandria tubes. When contact occurs, the heat is conducted through the fuel channel and calandria tube into the moderator D_2O, helping to maintain pressure tube integrity. As the temperature of the moderator increases, its capability as a heat sink would be reduced.

Neutronic considerations

It should be clear that controlling the moderator outlet temperature at 61°C does not mean that this is the highest temperature in the moderator. The bulk moderator temperature in the calandria is about 3°C higher than the outlet temperature. Temperatures within the calandria vary depending on location, and operating activities (e.g. fueling)

- As the temperature of the moderator increases, the moderator temperature coefficient (positive for equilibrium fuel) causes core reactivity to increase.

- If temperature increases to the point of localized boiling, the voiding decreases effective core lattice pitch (i.e. no moderation will occur in the steam bubbles). Since our reactors are over-moderated, this can cause core reactivity to increase until the boiling becomes excessive, which will then cause under-moderation.

- Boiling would initially be localized to hot spots and be very erratic. This leads to unstable reactivity effects in the core, localized to the boiling locations.

Explosion hazard

An elevated moderator temperature will cause the moderator cover gas D_2 levels to increase, as the D_2 comes out of solution. This can lead to an explosion hazard in the moderator cover gas

Metallurgy considerations

The thermal temperature range in the moderator must be established to minimize the thermal stresses between the end shield and the calandria. Damage to components (such as rolled joints, welds, etc.) could occur if these stresses become large.

2.2.4 Moderator Level

In order for the moderator to be able to achieve its design function, the moderator level must be sufficient to minimize neutron leakage from the core and cool the core components.

- Too low a moderator level will result in loss of reactivity, overheating of core components and an increased rate of D_2 evolution due to increased D_2O surface area exposed to the cover gas.

- In some stations ion chamber response may be affected and severe flux tilts result if power is maintained at reduced levels.

- Too high a level will result in insufficient space in the calandria to accommodate SDS2 firing without bursting a rupture disc. Possible flooding of the SDS2 He injection header can also occur, which can result in severe water hammer when SDS2 fires.

All CANDU reactors except for Pickering ‘A’, do not have a significant range of moderator level change before a safety action parameter is reached. At Pickering ‘A’ however, moderator level control could be utilized for reactivity control.

2.2.5 Abnormal Conditions

In this section, two abnormal conditions are discussed: loss of moderator cooling and a moderator heat exchanger leak.

Loss of Cooling

Loss of cooling to the moderator will cause the moderator temperature to rise. This could be caused by loss of moderator circulation flow or loss of cooling water to the moderator heat exchangers. This will result in the consequences listed earlier under moderator temperature /level control section.

Moderator Heat Exchanger Leak

In the case of a moderator heat exchanger leak, the moderator D_2O will be lost to the lake. This causes two operating problems:

a) There is a potential for highly tritiated D_2O reaching the environment. Continued operation may depend on the target of 1% of the Derived Emission Limit (DEL - regulatory limit) for the station.

b) An economic penalty exists for the D_2O loss from the station. Continued operation would also depend on the rate of leakage. If the leak is serious enough to require immediate repair, a shutdown will be required to drain and repair the leaking tube(s) or replace the HX tube bundle.

2.2.6 Summary of Key Concepts

- The major heat sources in the moderator while operating are from thermalizing neutrons, absorption of γ (from fission, fission products and activated core components) and conventional heat transfer mechanisms The major heat source in the moderator while shut down is from fission product and activated core component γ absorption and conventional heat transfers.

- The optimum temperatures for the moderator D_2O is 61°C at the outlet.

- If the moderator temperature is too low or too high, thermal stresses between the end shield and the calandria will be high, possibly causing equipment damage.

- If moderator temperatures are too high, reactivity will increase. Very high temperatures may cause localized boiling. This could cause reactivity control problems. At high temperatures the moderator would not be as effective as a heat sink in the event of a LOCA (if fuel channel sagging occurs, due to overheating, until contact with a calandria tubes is made). D_2 excursions can also occur due to high moderator temperatures.

- Normal moderator level must be sufficiently high to minimize neutron leakage and to ensure that core components are cooled.

- Too low a moderator level will result in loss of reactivity, overheating of core components and an increased rate of D_2 evolution due to increased D_2O surface area exposed to the cover gas. In some stations, ion chamber response may be affected.

- Too high a level will result in insufficient space in the calandria to accommodate SDS2 firing without bursting a rupture disc. Possible flooding of the SDS2 He injection header can also occur, which can result in severe water hammer when SDS2 fires.

- Loss of service water to the moderator heat exchangers or loss of moderator circulation flow will cause the moderator temperature to increase. The resultant moderator heating will eventually cause reactivity control problems, equipment overheating and damage. Also in this case the moderator may not be an effective heat sink in the event of a severe LOCA. As boiling occurs, pressure could also increase in the calandria, causing a rupture disc to burst. D_2 excursions and moderator level increases can occur due to loss of moderator cooling.

- A moderator heat exchanger leak will result in the loss of moderator D_2O. This represents a radiological emission concern and an economic penalty.

2.3 Cover Gas Circulation & Pressure Control

The purpose of the moderator cover gas system is to provide a non-corrosive/non-explosive atmosphere for the calandria components. It is for these reasons that helium is used for the moderator cover gas.

This section will cover the cover gas circulation requirements, cover gas purging, factors affecting cover gas D_2 concentrations and consequences of high D_2 and N_2 concentrations in the cover gas.

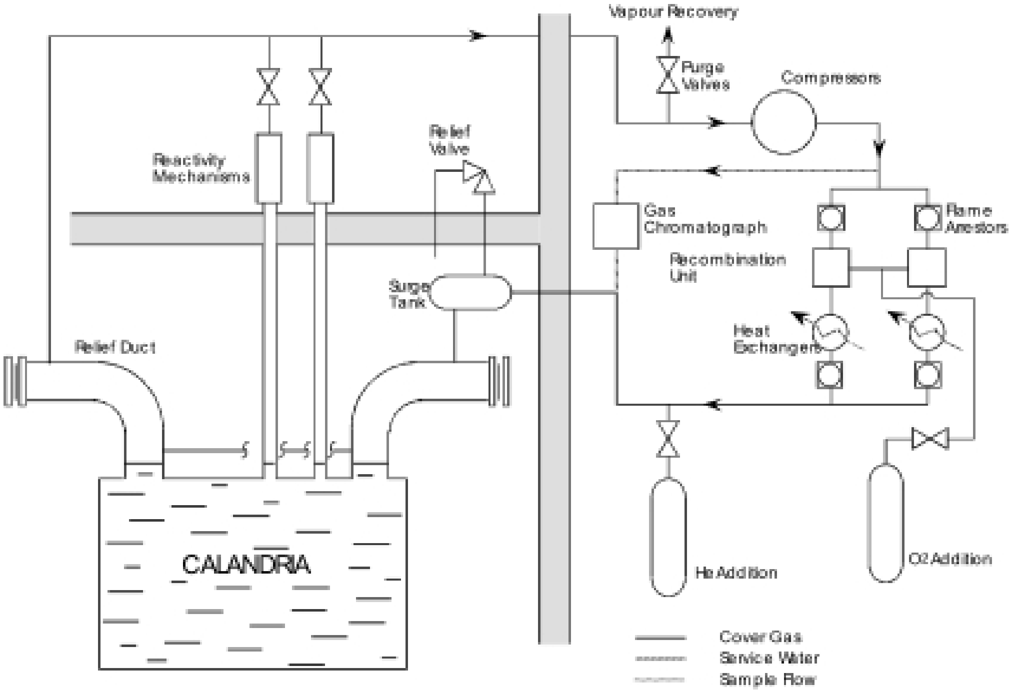


Figure 2.3
Simplified Moderator Cover Gas System

2.3.1 Explosive Limits

The cover gas system facilitates the recombination of D_2 and O_2 created due to radiolysis of the moderator D_2O. The explosion hazard is eliminated by keeping D_2 and O_2 levels within operating range, which are below the lower explosive limits of 8% D_2 and 5% O_2. Typical normal operating levels are maintained well below 1% D_2, with O_2 concentrations slightly higher to ensure a sufficient quantity of O_2 for recombination.

2.3.2 D_2 And O_2 Concentrations In The Cover gas

The rate of radiolysis and the rate at which the dissolved gases evolve from the moderator are affected by a number of factors.

The rate of radiolysis increases with increasing γ radiation. Thus, the higher the power level, the greater the rate at which radiolysis occurs. High conductivity or impurities (i.e., nitric acid, resin fines, oils, etc.) in the moderator will cause the natural rate of D_2 and O_2 aqueous recombination to decrease.

Once these gases are produced, the rate at which they come out of solution also depends on a number of other factors such as moderator temperature, moderator pressure, moderator level / surface area and the concentration of dissolved D_2 & O_2 in the moderator.

2.3.3 Cover Gas Circulation

All reactor states require the circulation of the cover gas. The reasons for the requirement of continuous circulation are:

a) High decay γ fields exist in the core during shutdowns, which will cause radiolysis to continue (hence allowing D_2 and O_2 concentrations to build up). This can be further aggravated by moderator poisons (impurities) which cause a decrease in the natural recombination rate. This is why D_2 concentrations in the cover gas increase during a reactor restart after an outage (i.e., radiolysis exceeds the low rate of natural recombination).

b) Continuous circulation also ensures that any samples taken from the cover gas are representative of the cover gas.

c) The circulation also ensures that a flow is maintained to the recombination units, which will recombine the D_2 and O_2 back into D_2O.

2.3.4 Cover Gas Purging

If, during a unit shutdown, the cover gas compressors require maintenance, a helium make-up supply and a method of purging must be available. This is to ensure that the removal of D_2 and O_2 can occur (i.e., without circulation of the cover gas through the recombination units).

Purging the cover gas is also the only method of removing air or N_2 from the cover gas. This is of particular concern when the system has been opened for maintenance, i.e., where air ingress has occurred.

Purging of the cover gas is carried out during reactor operation when concentrations of N_2 or D_2 exceed limits specified in your operating documentation. This is accomplished by bleeding off helium from the system, while making up helium to the system at the same rate (to prevent a drop in cover gas pressure).

When purging the cover gas, care must be taken to ensure that the pressure is not reduced (i.e., the normal pressure is maintained at ~10-25 kPa(g)). Recall that lowering the pressure in the cover gas system can cause an increase in D_2 concentration in the cover gas (and evolution of dissolved gases in general).

2.3.5 Cover Gas Monitoring

The cover gas can be monitored by two methods:

a) The first is by the on line gas chromatograph, which takes samples upstream and downstream of the recombination units. This will give the operator warning when D_2, O_2 and N_2 concentrations are out of specified ranges. The D_2 and O_2 readings across the recombination units will also indicate to the operator that these units are functioning properly.

b) The other method of sampling is a manual grab sample of the cover gas. This manual sample will require analysis by the chem lab.

2.3.6 Abnormal Conditions

Concentration of D_2 between 2% and 4% in the cover gas requires that conditions be established to ensure D_2 levels do not increase further. This prevents an explosive mixture of D_2 and O_2 being formed. The required methods vary from station to station, but typically include the following.

- Purging of the cover gas;

- Adding O_2 to ensure there is a sufficient quantity for recombination;

- Check cover gas compressor operation and place another compressor in service if required;

- Check recombination unit operation. This could be accomplished by checking that recombination unit temperature is in the correct range, i.e., recombination of D_2 and O_2 produces heat. If the recombination unit catalyst becomes wet, the unit will not function (which would require the heaters to be put in service until the unit is functioning). Operation could also be confirmed by D_2 and O_2 levels at the inlet/outlet of the recombination units. If there is a fault with the unit, another unit would have to be placed in service;

- Lowering the moderator temperature;

- Increase moderator level;

- Increase purification or place fresh IX columns in service;

- Do not raise reactor power.

At a concentration of 4% D_2 in the cover gas, the required actions are, again, to ensure that the concentration does not reach the explosive limit. Here, the actions are a bit more drastic, as the margin to the explosive limits of D_2 and O_2 is being reduced The typical methods to reduce D_2 levels will include the following.

- continue purging of the cover gas,
- sample immediately and after the D_2 concentration has been confirmed above 4%, shutdown the unit in a controlled manner.

Nitrogen in the cover gas can form nitric acid in the presence of moisture and radiation. This acid will also increase radiolysis of them moderator D_2O. This could cause a D_2 excursion, resulting in a plant shutdown. Note that this acid will also cause corrosion of the moderator components. The N_2 concentration is maintained $\leq$ 2%, the typical methods to reduce N_2 levels will include:

- Purging the cover gas system until N_2 is within specifications;
- Increasing moderator purification to remove any acids that have formed.

2.3.7 Summary Of The Key Concepts

- D_2 concentration in the cover gas increases with:
  - Moderator temperature. As the moderator temperature increases, the D_2 solubility decreases.
  - Decreased moderator cover gas pressure. As the pressure of the cover gas decreases, the D_2 solubility decreases.
  - Decreased moderator level. As the moderator level decreases, the surface area of the moderator exposed to the cover gas increases. This increased surface area makes it easier for the D_2 gas to come out of solution.
  - Increased reactor power. As reactor power increases, so do the γ and neutron fields. The increased fields increase radiolysis.

  - Increased impurities in the moderator. An increase in the impurity level in the moderator will cause the rate of radiolytic recombination to reduce.

  - Moderator D_2 concentration. As the moderator D_2 concentration increases, the D_2 will reach a new equilibrium with the cover gas, resulting in a higher rate of gas evolution from the moderator to the cover gas.

- The lower explosive limits for D_2 and O_2 in a helium environment are 8% D_2 and 5% O_2.

- All reactor states require cover gas circulation. Radiolysis continues during reactor shutdown due to high decay γ fields in the core.

- Purging of the cover gas is required when:

  - Cover gas N_2 or D_2 concentrations are high.

  - The system has been opened for maintenance. This is to purge air (which is mainly N_2) from the cover gas to prevent nitric acid from being formed.

  - Cover gas compressors are not available to circulate the cover gas through the recombination units.

- When purging the cover gas system, care must be taken to ensure that system pressure is not lowered, which could cause a D_2 excursion.

- D_2, O_2 and N_2 concentrations are monitored on line by the gas chromatograph. Grab samples for chem lab analysis can also be taken.

- D_2 concentrations between 2% and 4% may typically require the following to reduce concentrations:

  - Purging of the cover gas

  - Adding O_2 to ensure there is a sufficient quantity for recombination,

  - Check and place another recombination unit in service as required**,**

  - Check and place another cover gas compressor in service as required,
  - Increasing the moderator level,
  - Lowering the moderator temperature,
  - Keeping reactor power constant.

- Confirmed D_2 concentrations above 4% will require a shutdown (while the purge continues).

- N_2 concentrations above 2% will require a cover gas purge, and may require an increased rate of moderator purification to remove nitric acid that has formed.

2.4 The Moderator Liquid Poison System

The moderator liquid poison system is used for reactivity control. Soluble neutron poisons, with large neutron capture cross-sections to absorb neutrons, are added into the moderator in a controlled manner.

Poison may be added for the following reasons:

a) For fresh fuel burnup simulation. The poison compensates for excess fuel reactivity for the first 200 full power days of operation by the addition of a matching negative mk worth of poison.

b) For xenon equilibrium load simulation. Poison is added to compensate for the lack of xenon negative reactivity following a shutdown of about 30 hours or greater. The full xenon equilibrium load may be up to the full 28 mk worth at full power.

c) To overpoison the reactor during a shutdown to obtain a guaranteed shutdown state.

d) To compensate for reactivity due to overfuelling, sometimes called fuelling machine reactivity banking. The additional poison is added to match the extra reactivity from the fresh fuel. This is done to allow fuelling machine outages.

2.4.1 System Description

A sketch of the general system is shown in Figure 2.4. The poison mixing tanks are located in an accessible area while on power. A delay tank is installed in the supply line to allow the gamma fields from nitrogen-16 (N^{16}) and oxygen-19 (O^{19}) isotopes to decay to acceptable levels when the mixing tanks are filled from the moderator system during operation. The poison tanks are equipped with agitators, level gauges, sample valves, poison addition ports and vent lines and vent traps. Most of this equipment is used in the refilling of the mixing tanks. The agitator, in particular, provides for good mixing and dissolution of poisons. Boron is of particular concern because of its low solubility.

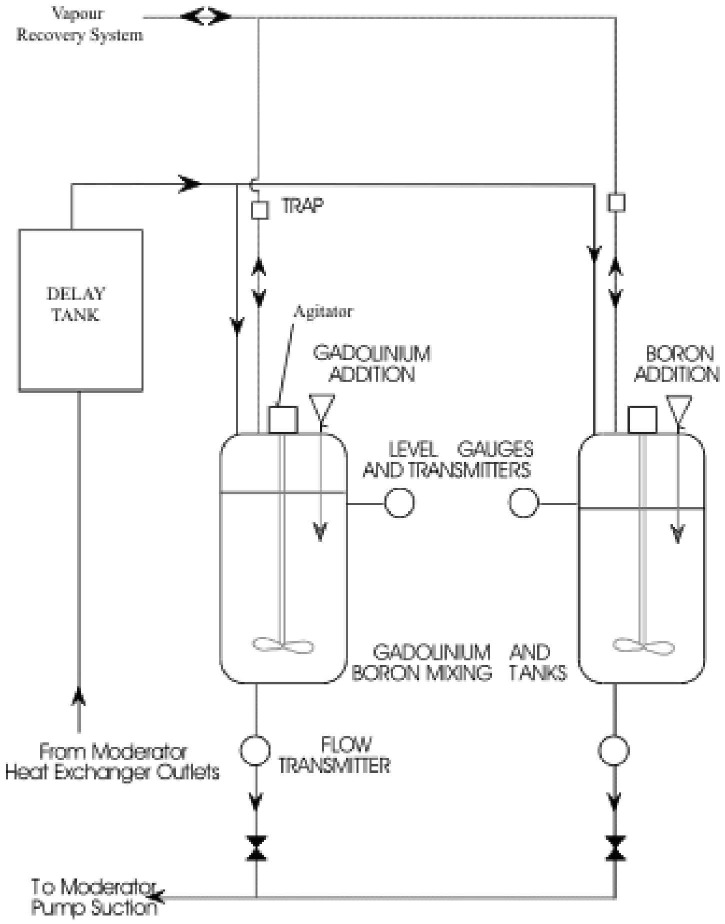


Figure 2.4
Typical moderator Poison Addition System

2.4.2 Normal Operation

Choice of Poison

Generally two neutron absorbing poisons are used in the moderator liquid poison system. Depending upon their nuclear and chemical properties, one poison may be more appropriate for a particular application than the other. Table 4.1 summarizes a comparison of the two poisons

Table 2.1
Comparison of Poisons

POISON	ADVANTAGES	DISADVANTAGES
Boron (B)	• Preferred for longer term (days) operations due to slower burnout (little makeup needed) and due to slower IX removal • Smaller mk/kg poison in case of inadvertent addition (i.e. weaker poison • Because of lower conductivity in solution than Gd, it will not result in a cover gas D_2 excursion.	• Less soluble than Gd, undissolved solid could block lines and reduce (unsafely) -ve Δk worth in system. • Uses more IX resin to remove than Gd, per mk worth.
Gadolinium (Gd)	• Preferred for short term operations (<2 days) due to more rapid burnout and more rapid IX removal. • High solubility allows high mk to be achieved without poison precipitating out. • Uses less IX resin to remove than B, per mk worth.	• Conductivity in solution is higher than B. This increases the risk of D_2 excursions due to reduction of natural aqueous recombination • More rapid -ve reactivity insertion (stronger per kg poison) in the case of inadvertent addition. • Will precipitate out when solution pH is >7.

Table 2.2:
Specific Applications of Moderator Poisons

APPLICATION	POISON & WHY CHOSEN	WHY POISON ADDED
Fresh fuel burnup simulation - prior to initial startup and during initial operation when the unit contains fresh fuel	Boron - slow boron burnup rate in neutron fields and slow IX boron removal rate closely match slow fuel burnup rate and slow fuel fission product buildup.	To compensate for <u>extra</u> reactivity of fresh fuel, due to absence of longer lived fission product poisons and to compensate for the pending plutonium peak in fresh fuel.
During fuelling	Boron - burnup rate and removal rate of boron more closely match reactivity changes of new fuel.	To compensate for the extra reactivity of new fresh bundles, in part due to absence of longer lived fission product poisons.
During overfuelling (fuelling machine reactivity shim control)	Boron -again burnup rate and removal rate of boron more closely match reactivity changes of new fuel	To compensate for extra reactivity of the excess fuel
During an extended outage	Gadolinium -IX removal rate is faster. Gadolinium is more soluble than boron and has a higher negative mk worth per ppm dissolved. Gd usually does not precipitate unless pH>7.	To make the reactor deeply subcritical. To compensate for loss of xenon and reactivity effects.
Following startup after a poison outage (xenon transient)	Gadolinium - xenon will buildup at almost the same rate as gadolinium is burned out in neutron flux. The slight mismatch can be compensated by adding Gd from Gd tank or removing Gd with IX column.	To compensate for lack of xenon after the poison outage.
After a large increase in power following sustained operation at a lower power level	Gadolinium - will burnout at almost the same rate as xenon builds up.	Large increase in power after sustained low power operation will initially decrease the xenon level due to increased neutron flux. The poison, if required, will compensate for the loss of xenon. Xenon will, over time, increase to a new higher equilibrium concentration.

Use of poison during a startup following an extended outage includes two durations:

1. Startup following a shutdown of longer than three days,

A startup to full power following 3 or more days after a shutdown may begin with effectively no xenon in the core as shown in Figure 2.5. The xenon will buildup to about -28 mk worth of reactivity at almost the same rate as gadolinium is burned out by neutron flux removal alone. The match will not be exact as indicated by changes in the average zone level. Any mismatch can be compensated by adding more gadolinium or removing gadolinium by valving in the Gd IX column.

2. Startup between 1.5 and 3 days after a shutdown.

A startup to full power following 1.5 to 3 days of shutdown from full power, will have a xenon concentration as shown by Figure 2.6. Gadolinium must be added as shown during the xenon burnout period. During the subsequent xenon buildup, the gadolinium will burn out at about the same rate. Any mismatch is again detected by the average zone level and is controlled by gadolinium addition or removal as previously discussed. Startup at about 35 hours following shutdown is shown in Figure 2.6.

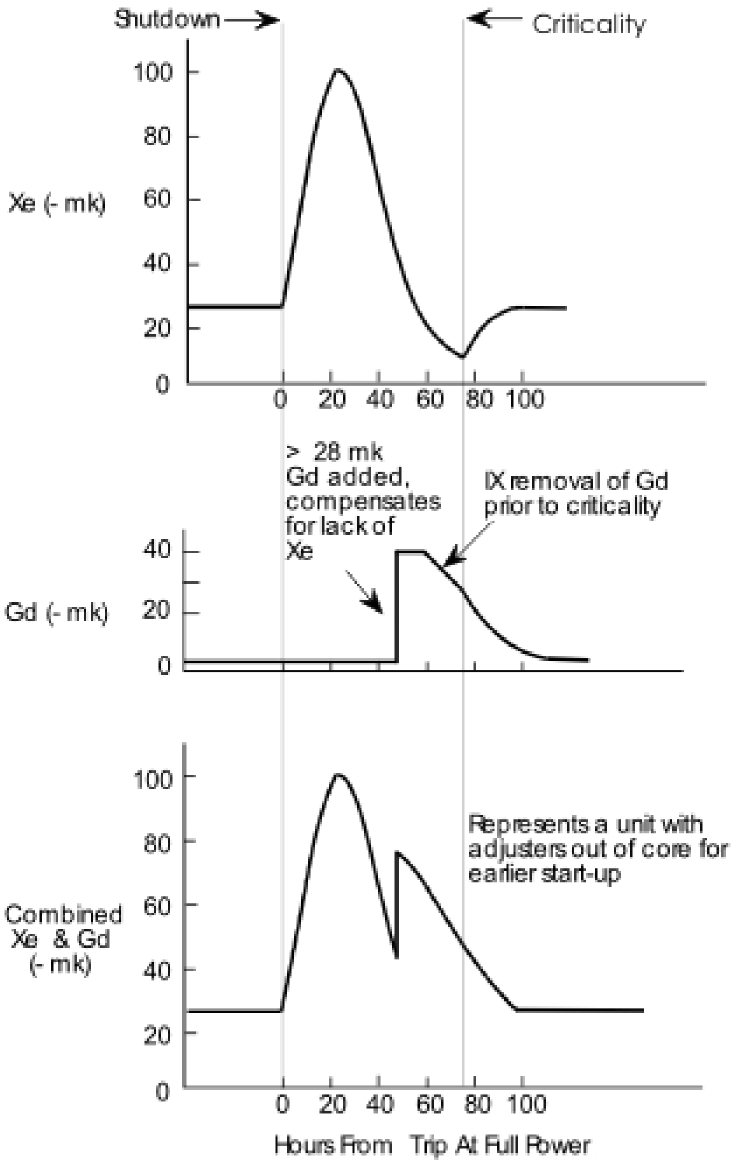


Figure 2.5

Gd Concentration in Moderator after a Shutdown of about 3 days

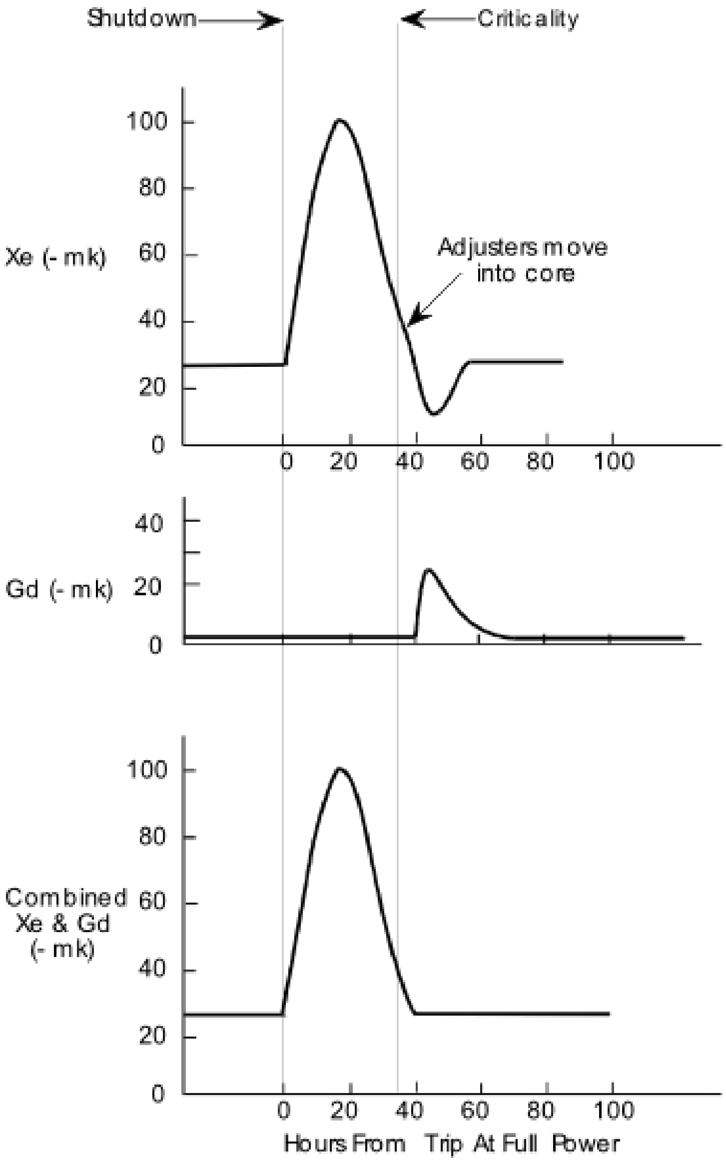


Figure 2.6
Gd Concentration in Moderator for a Startup 2-3 Days After a Shutdown

2.4.3 Monitoring and Control

Manual addition of poison to the moderator is usually done from the control room, although it can also be added from the field. To monitor and control poison addition, the control room operator has four general indications:

- The position of the handswitches for the motorized valves on the liquid poison addition lines, downstream of the mixing tanks

- Liquid poison flow rate, from the flow transmitter

- Poison tank level, from the level transmitters with backup from the level gauges in the field

- Average liquid zone response to the poison addition

To ensure that the correct amount of poison has been added for conditions requiring poison, there are two sources of information generally available:

1. Ensuring that the average zone level is in an acceptable controlling range for RRS if operating

2. Sampling the moderator system for poison concentration using chem lab analysis when shutdown.

When poison is added while the reactor is critical, for any of the following reasons such as, initial startup with fresh fuel, fuelling, or a xenon transient, it is appropriate to monitor the average zone level. This will determine if it is necessary to add or remove poison to ensure the zone levels remain in an acceptable controlling range.

During an extended outage or guaranteed shutdown state, to ensure that the poison level is appropriate, it will be necessary to sample the moderator system for poison concentration using chem lab analysis. Since the zones are no longer controlling in this state and the reactor is deeply subcritical, zone level will no longer indicate poison level.

Chem lab sampling will give a good indication of the actual poison concentration available since only slight irradiation of the poison has taken place. However, when the poisons are irradiated, the neutron absorbing isotopes burn out. The chemical concentration of poison will no longer be related to the mk worth of the poison. Thus sampling during a xenon transient or fuelling reactivity banking, will not clearly indicate whether sufficient poison is in the moderator to provide the mk worth required. Figures 2.7. and 2.8, indicate how poison concentration and poison mk worth vary with irradiation time. Figure 2.7. shows the variation of boron mk worth and boron chemical concentration with irradiation time. Figure 2.8 shows the same variations for Gd.

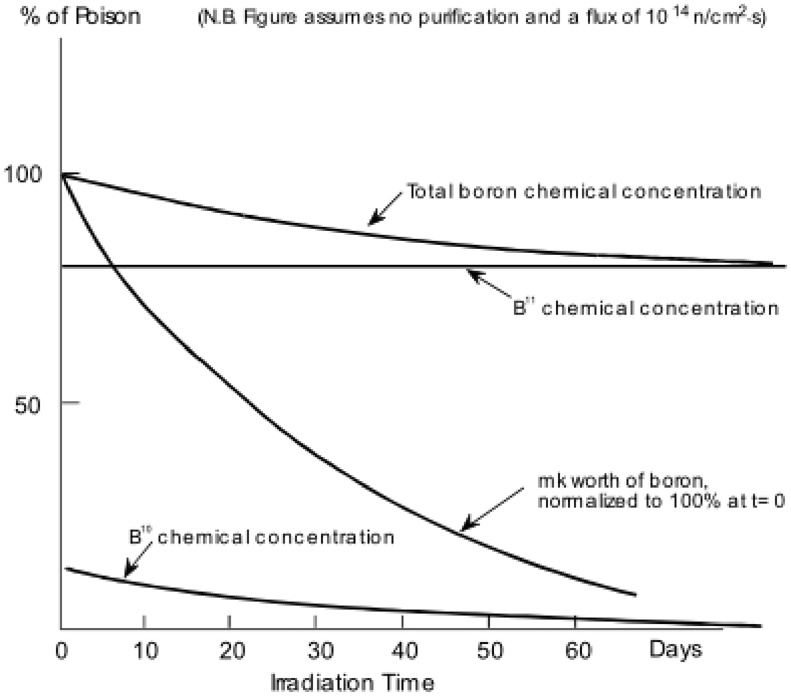


Figure 2.7
Variation of Boron mk Worth and Boron Chemical Concentration with Irradiation Time

Most plants provide an automatic gadolinium addition feature, where the reactor regulating system regulates the poison addition. This is done automatically by RRS to control reactor power during a slow uncontrolled increase in reactor power. The automatic addition feature is intended to return the reactor to the controlling range after the zones have filled and the absorbers have been inserted.

At some stations, automatic poison addition may also be initiated if the pressurizer level is low shortly after moderator cover gas pressure becomes high (this is indicative of a possible pressure tube failure).

There is no automatic addition feature for boron. It must be added manually.

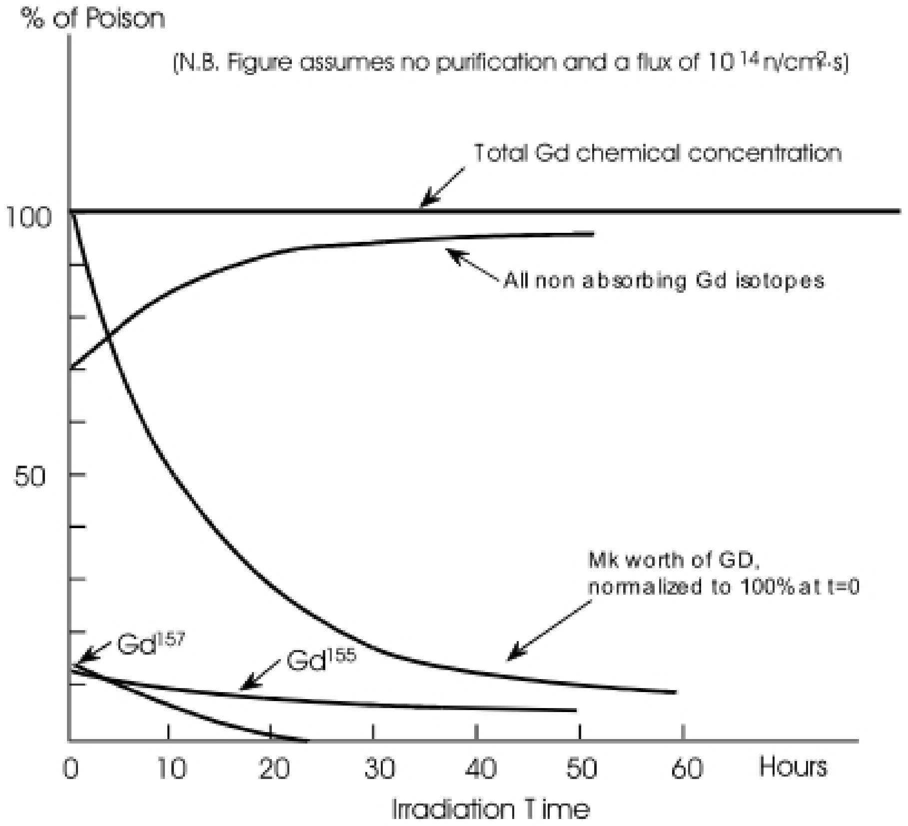


Figure 2.8
Variation in Gadolinium mk Worth and Chemical Concentration with Irradiation Time

2.4.4 Abnormal Operational Situations

There are five unusual operational situations for the moderator liquid poison system which will be discussed.

Inadvertent poison addition at full power

When poison is added inadvertently, the following effects of major concern to operation of the unit are likely to occur:

1. i) Loss of normal zone control - the liquid zones will drain to remove light water, a neutron absorber, to compensate for the poison addition. This may lead to other reactivity device movement to compensate for zone draining or loss of spatial control if the adjusters do not drive out.

2. ii) Exceeding poison licensing limit - an upper limit to the moderator poison load at high power and equilibrium conditions exists, to prevent excess positive reactivity from occurring in event of in-core LOCA in the heat transport system.

3. iii) Poison outage - if the amount of negative reactivity added cannot be compensated for, a forced outage will occur.

Inadvertent poison removal at full power

When poison is removed inadvertently from the moderator, the average zone level will rise to compensate for the poison removal. When the zones fill, absorbers will drive in for further negative reactivity to bring the zones back into control. If more poison is still removed, RRS, in most units, will automatically add gadolinium to insert negative reactivity. Even though power is controlled, a unit upset will result from this event.

Inadvertent poison removal at startup

With inadvertent poison removal during startup, the reactor will reach criticality much faster than normally expected. Power again would eventually be controlled, with a unit upset resulting.

Boron use where gadolinium preferred

Gadolinium is generally preferred for short-term effects such as replacement of xenon poison effects. The use of boron instead, would increase the poison removal time. The burnup time for boron is much longer than for gadolinium increasing its removal by this method. Boron removal by the purification IX columns is slower and requires more IX columns which in turn is more costly. In fact, purification should be available and in service when boron is inserted. With gadolinium, it is not as important to have the purification system operating as burnup will occur more quickly than the boron.

Poison Unavailability

With the liquid poison addition system unavailable, the normal full power poison addition situations discussed previously, would be handled with increased difficulty. Where boron addition is unavailable, it becomes difficult to compensate for extra reactivity from fresh fuel or fuelling ahead. Where gadolinium addition is unavailable, it becomes difficult to compensate for xenon following a xenon transient. Unit operation at full power would most likely continue, but replanning of the operating strategy may be necessary.

2.4.5 ***Summary Of The Key Concepts***

- Boron is added to the moderator, prior to initial startup when the reactor contains fresh fuel. It may also be added during fuelling, or during overfuelling. Boron has a slower burnup rate, which closely matches the fuel burnup rate and fission product buildup. Poison is necessary to compensate for extra reactivity of fresh fuel.

- Gadolinium is added for extended outages because its removal is faster. Poison is necessary to keep the reactor subcritical and compensate for the loss of xenon.

- Following startup after a poison outage and, after a large increase in power following sustained operation at a lower power level, gadolinium is added since it burns up at about the same rate that xenon builds up. Poison is required to compensate for the lack of, or reduced xenon levels in the fuel.

- When poison is added manually, the control room operator can monitor and control the position of the handswitches for the motorized valves on the liquid poison addition lines, as well as monitor poison flow rate, poison tank level, and average liquid zone response to the poison addition.

- To ensure the proper amount of poison has been added when the reactor is critical, the average zone level should be monitored. During an extended outage, or guaranteed shutdown state, the moderator system poison level should be sampled using chem lab analysis.

- Gadolinium is added automatically by RRS, in most units, to control reactor power during a slow uncontrolled increase in reactor power.

- If poison is removed inadvertently at full power, the average zone level will rise. A unit upset may result from this event.

- If poison is removed inadvertently during startup, criticality may occur much faster than normally expected, with a unit upset again possible.

- If boron were added when gadolinium was the preferred poison, the poison removal time would increase substantially because of a longer IX removal time and longer burnup time. Increased cost of removal is also a concern.

- If a poison unavailability occurs, the normal full power poison addition situations could not be handled, which may affect operating flexibility.

2.5 *The Moderator Purification System*

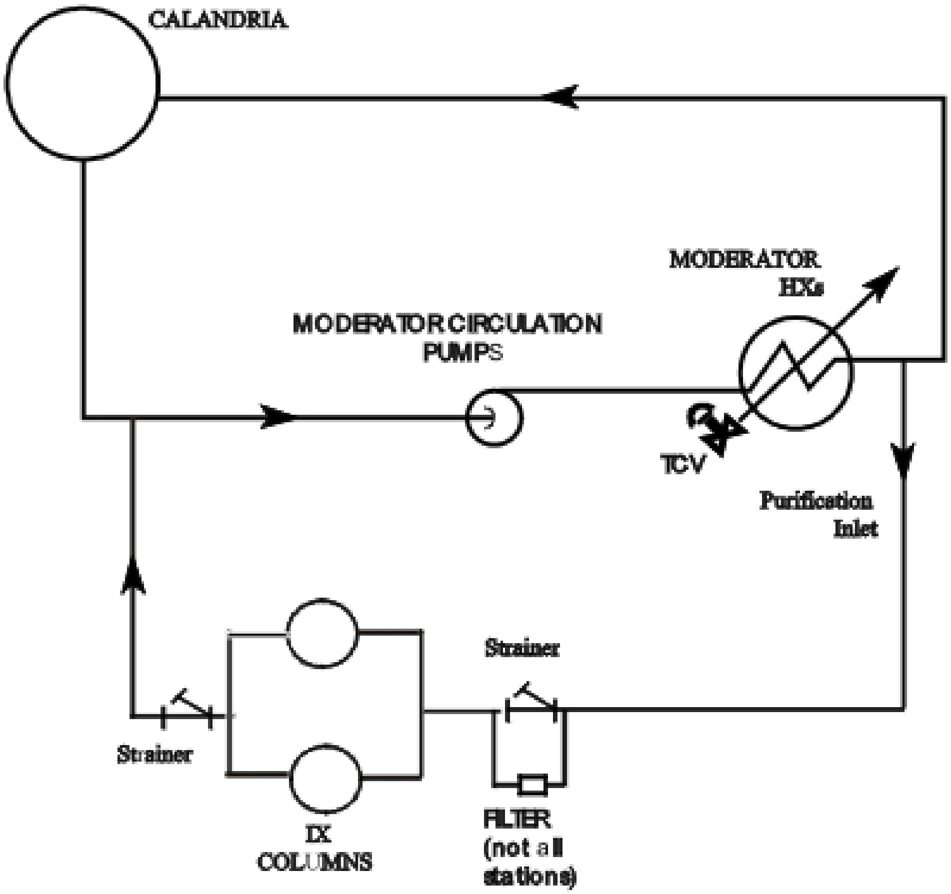


Figure 2.11
Typical Moderator Purification System

In this section, you will learn about methods used to remove moderator impurities. Three modes of system operation are described: normal cleanup, gadolinium removal, and boron removal.

The important operating parameters that must be maintained in any of the above modes of operation will also be discussed.

2.5.1 Moderator Purity

Corrosion products, as impurities to the system, appear as suspended material and dissolved ions. Ions may also be purposely added as neutron absorbing poisons for reactivity control or shutdown. Over the long term, the function of the purification system is to keep the moderator D_2O relatively free of foreign material to ensure: D_2 explosion hazard is minimized by reduced radiolysis, low corrosion, and low neutron absorption.

This function is accomplished in three ways.

1. Controlling pH,
2. Use of strainers and filters,
3. Use of ion exchange columns

The pH is maintained around 7, mainly to ensure that moderator poisons do not precipitate out of solution, but also to minimize corrosion of stainless steel components.

There are strainers situated on the inlet and outlet of the ion exchange columns. They will remove particulate material that may be in the system, especially any resin fines. Some stations have a filter at the inlet to the purification loop as well, to collect any corrosion products or suspended material.

The ion exchange columns will remove soluble impurities to reduce conductivity as discussed under the heading conductivity. These are usually mixed bed resins removing positive and negative ions (cations and anions).

2.5.2 Modes of System Operation

Removal of gadolinium and boron may employ strong acid/strong base resins as well as different removal techniques. Gadolinium forms strongly charged ions in solution, which are easily attracted to ion exchange columns. Boron, however, forms weakly charged ions in solution which are not as easily removed by ion exchange columns.

Normal Cleanup

To ensure that the ion exchange column removes all ions during normal cleanup, the specification of overall conductivity is monitored. Some specific ions of concern are also monitored including chloride, nitrate, gadolinium, and radionuclides. Continuous flow through one IX column is adequate to maintain these specifications. The actual flow rate varies from station to station but is most often in the 5 to 7 kg/s range per column. Exceeding this may lead to resin damage and subsequent dispersal of resin fines into the moderator system. If increased flow is required for cleanup, an additional column must be valved in to service.

A normal cleanup IX column will not be very efficient in removing boron, but will remove any of the above-mentioned ions.

Gadolinium Removal

IX resins remove gadolinium easily because it is strongly ionized. For strong ions, the concept of purification half-life applies. This term refers to the time required to reduce the ion concentration to one half of the starting value. The time for gadolinium cleanup half-life will depend upon the purification flow rate and the total mass of the moderator D_2O. For any unit, the only normal variable is purification flow rate, which in turn is dependent upon the number of columns in service.

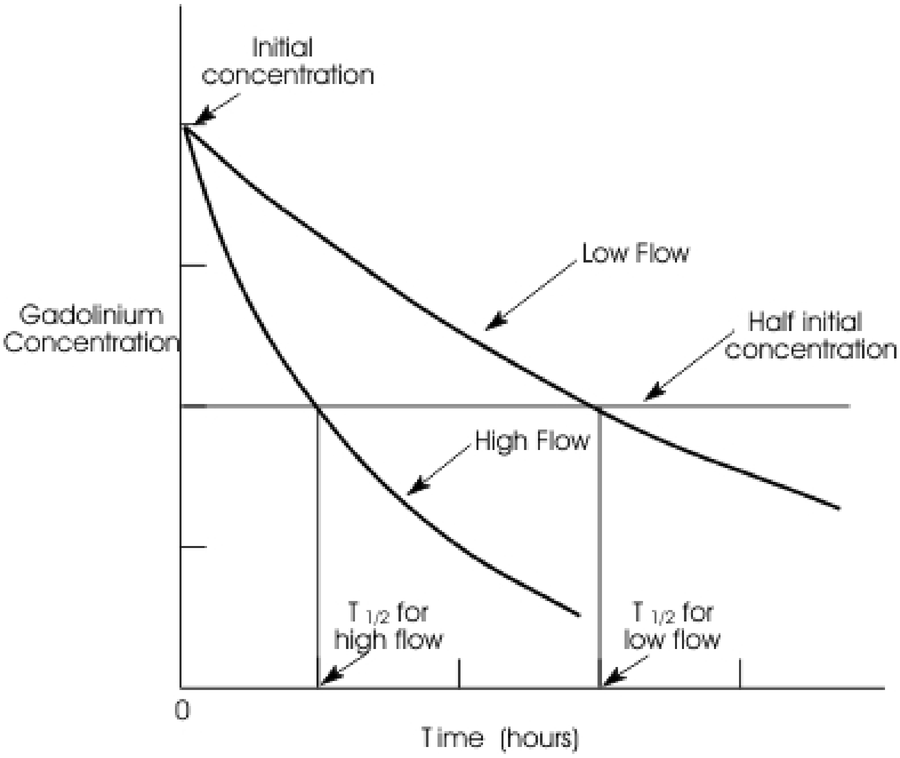


Figure 2.10
Typical Moderator Purification Half Life for Different Purification Flows

Figure 2.10 illustrates the relationship for gadolinium concentration versus time for different purification flows. The time to reduce the initial concentration to one half is indicated as purification half-life for different purification flows. Of course, to increase the purification flow significantly, the number of parallel IX columns in service must also increase.

When the poison injection system operates to shut down the reactor, it inserts as much as 600 mk of negative reactivity in to the moderator. For example, with a flow rate of 20 kg/s, one cleanup half-life will take about 3 ½ hours. Five half-lives will reduce the gadolinium to -19mk. Five half-lives would take 17 ½ hours at this flow rate. This cleanup time is too long to prevent a poison outage. However, when this cleanup time is combined with the time to repoise SDS2, 40 to 45 hours will have elapsed. This is enough time to allow the xenon to decay to startup levels.

When gadolinium has been added for xenon simulation, the burnup rate closely matches the rate at which xenon reactivity builds up, so that purification removal is not initially required. Gadolinium poison concentration naturally decreases in neutron fields, with a burnout half-life of about 8 hours initially, and longer as the largest cross-section isotope burns up. Average zone level fluctuations will indicate any imbalance between the two rates. When the poison has burned out and xenon has built up to its normal level, the gadolinium isotopes must be removed by normal cleanup to keep the moderator D_2O conductivity within specification.

Boron Removal

Because boron forms a weak ion in solution, its removal is more difficult and time consuming. The removal rate depends upon the difference between the boron concentration in solution and the boron concentration in the IX column. An IX column removing boron from the moderator will, over time, reach equilibrium with the boron in solution, so that no further boron can be removed. The column is said to be saturated or borated. In the same way, an IX column with a boron concentration higher than that of the moderator will form an equilibrium concentration with the solution and give off boron to the moderator water. Establishing equilibrium concentrations with the solution only occurs with weakly ionized substances and does not occur when a strong ion, such as gadolinium, is attached to an IX column.

Because boron (B) establishes an equilibrium concentration with the solution, it is removed from the moderator in a multistage IX technique using 2 or 3 IX columns operating on different moderator boron concentrations. An example of this would be a two-stage removal of 3mg B/kg D_2O or 28 mk worth. One column may reduce the concentration down to 0.5 mg B/kg D_2O at which point it becomes saturated. The column is then isolated and a fresh column is used for the second stage of boron removal to reduce the boron concentration further. This column is then used the next time for first stage boron removal, to maximize the use of the resin. A general rule of thumb for boron removal is that a fresh IX column will leave at least 1/7th of the original boron concentration after the column saturates.

Thus the rate of Boron removal cannot be determined by the normal half-life curve of Figure 2.10, since there are other factors beside purification flow rate and total mass of moderator D_2O. Boron removal capacity of the IX columns is also sensitive to temperature. An increase of a few degrees in the IX column will lower the equilibrium concentration in the IX column, reducing its capacity for boron. In fact, it may even release boron from the resin.

Boron concentrations decrease slowly in neutron fields, with a burnout half-life of 1 to 20 days depending upon reactor flux. Because of the long burnout time period, IX columns may be required to remove boron. Normal cleanup is required even when boron is burned out to reduce the conductivity effects on the moderator.

If boron or gadolinium are kept in the moderator when their reactivity effects are no longer required, additional positive reactivity must be provided to counter the poison effects. The normal reactivity control span the average liquid zone level may not allow the zones to accommodate all reactivity effects. Keeping gadolinium in the moderator when it is no longer required will also keep the conductivity high, contributing to increased radiolysis products. The third concern is financial. Fuel costs increase when operating with extra poison.

2.5.3 Operating Parameters

In this section, four important parameters that characterize system operation are discussed: purification flow, inlet temperature, pressure, and moderator conductivity.

For each of these parameters, you will learn how it is maintained and what adverse consequences occur when this parameter goes beyond its limit.

Purification Flow

CANDU stations use a bypass flow purification system around the moderator circulating pumps as shown in Figure 2.9.

Usually, the purification inlet is downstream from the moderator heat exchanger discharge. The moderator pump differential pressure is used as the driving force for the purification loop. Typically 4 to 6 columns are available for use in parallel. The extra columns allow for slurrying of resin from a spent column while purification is ongoing. The number of columns in service depends on the poison removal requirements.

Typical purification flow ranges from 5 to 25 kg/s, depending upon the number of IX columns in service (and station). Exceeding recommended flow rates can lead to resin damage. An individual column inlet motorized valve is the isolation for the column.

In some stations, it has been found that with high flows, the quantity of resin fines increase due to mechanical breakdown. The fines can be carried through to the IX discharge strainer and cause it to clog. The ion exchange process is also less efficient at higher flows.

Low purification flow would take a longer time for moderator clean-up. In fact, for very low flows, the rate at which impurities are produced may exceed the purification rate so that even though purification is occurring, the impurity level may be increasing.

Inlet temperature

Most stations take advantage of the cooling provided by the moderator heat exchanger. The purification inlet is downstream of the main moderator heat exchanger outlet. IX resins are temperature sensitive. They should be kept below about 60°C to prevent damage and subsequent release of contaminants such as chlorides, boron, and gadolinium. Borated IX columns are particularly sensitive to temperature changes when they are at equilibrium with the moderator D_2O. A small temperature increase can release boron poison into the system. Typical purification inlet temperatures are 30°C to 35°C.

Pressure

The moderator circulation pumps maintain the moderator purification pressure. The pump differential pressure is at least 650 kPa with the pressure reduced at the calandria by flow restricting devices. Since a typical system purification pressure drop is about 400 kPa, the pump differential pressure will provide sufficient pressure for an adequate flow. When the ΔP across an individual strainer (filter) increases, this component requires changing or cleaning. If they are not changed, the flow will gradually decrease until no purification flow occurs.

Conductivity

Moderator conductivity is a measure of the concentration of ionic impurities. It is monitored by in-line conductivity cells and by chem lab sampling. Conductivity must be kept low because as dissolved impurities increase the natural rate of D_2 and O_2 recombination decreases. In addition, increased neutron absorption and possible corrosion will result.

The conductivity is usually kept below 0.1 mS/m by continuous IX purification. An increase in moderator conductivity normally indicates spent IX resin in the column. Other methods that may identify that an IX column is spent are:

- Checking for high ΔP across the IX column (plugging),
- Observing average zone level reduction (boron leaching from resin),

- Checking for increased chloride readings at the column outlet.

The continued use of spent resin for purification will result in increased conductivity at the outlet that in turn can cause a D_2 excursion. This is because impurities are not removed or further impurities may be released from the resins. Other ways of detecting spent resin are indicated above.

Continued use of a saturated boron column will not reduce the boron content further. In fact, as ionic impurities replace the loosely bonded boron, more boron poison and contaminant is released to the system.

Another contribution factor to conductivity is resin fines escaping into the main moderator system. If not removed, they will increase conductivity by releasing ions to solution. Increased conductivity results in increased radiolysis products, producing a higher D_2 concentration and possible D_2 excursion. If D_2 levels in the cover gas are high, an explosion hazard may exist, prompting a unit shutdown.

2.5.4 Operation During Guaranteed Shutdown State

One method of placing the reactor in the guaranteed shutdown state is by adding an excess of neutron absorbing poison to the moderator to ensure that the reactor will not reach criticality. During this state, the moderator purification system must be isolated as part of the guaranteed shutdown state. This is to ensure that the poison will not be removed inadvertently.

2.5.5 Summary Of The Key Concepts

- Moderator purity is maintained to minimize radiolysis products, corrosion, and neutron absorption. Neutral pH control, strainers and filters, and ion exchange columns control moderator purity.

- Purification half-life refers to the time required to reduce the ion concentration to one half of its original value.

- Gadolinium removal depends upon purification flow rate.

- Boron is removed in a multistage technique because ion exchange columns easily saturate with boron.

- Boron or gadolinium should be removed when they re no longer required because the normal reactivity control span may be affected. Gadolinium nitrate contributes to the conductivity which in turn causes increased radiolysis products. Both poisons can produce increased fuel costs.

- Flow is maintained by using the main moderator circulation pump ΔP as the driving force for the purification loop. High purification flows result in a less efficient exchange process and may damage resin leading to plugged strainers or filters and increased impurities in the moderator. Low purification flow may not remove impurities as fast as they are formed.

- Ion exchange inlet temperature must be controlled to ensure high inlet temperature does not damage the resin. Boron removal columns are particularly sensitive to boron release when temperature is increased.

- Purification pressure is maintained by using the main moderator pump discharge pressure and monitoring the ΔP across components in the purification loop. High ΔP will result in reduced purification flow.

- The IX columns maintain low conductivity. Outlet conductivity and other parameters are sampled by the Chem Lab to determine if the column is spent. Continued use of a spent resin will result in increased outlet conductivity. Other indications of a spent resin include reduced IX flow (damaged resin), decreasing zone levels, or increased chloride levels. Continued use of a saturated boron column may release more boron into the system as it is displaced by stronger ionic impurities on the column.

- Resin escape into the moderator may contribute to cover gas D_2 excursions.

- The moderator purification system is isolated as part of the overpoisoned guaranteed shutdown state to ensure the poison will not be removed inadvertently.

2.6 Assignment

2.6.1 Moderator Water

2. Indicate one way that control room staff may be alerted to a low isotopic.

3. What will occur if the moderator isotopic is suddenly downgraded by:

   a) $\leq 0.3\%$

   b) $> 0.3\%$

4. Describe radiological hazards from moderator water contained in the pipe work and spilled moderator D_2O. Discuss both shutdown and high power operation states.

5. Describe 2 ways the moderator system be used to guarantee that a reactor is shutdown

2.6.2 Moderator Circulation System

6. Describe four consequences of exceeding the outlet temperature of the moderator.

7. State two circumstances that could result in loss of cooling to the moderator.

8. Describe five consequences of a moderator loss of heat sink.

9. Describe two adverse consequences of a moderator heat exchanger leak.

2.6.3 Cover Gas System

10. State the lower explosive limit of oxygen and deuterium in the cover gas.

11. Explain how each of the following factors affects the concentration of D_2 in the cover gas.

    a) Reactor power

    b) Moderator impurity levels

    c) Moderator temperature

   d) Cover gas pressure

   e) Moderator level

   f) Concentration of D_2 in the moderator

12. Explain why the cover gas must be circulated when the reactor is shutdown .

13. Give three circumstances that will require purging of the moderator cover gas.

14. Explain a precaution that must be taken when purging the cover gas.

15. State the two methods of monitoring the concentrations of D_2 O_2 and N_2 in the cover gas..

16. Explain the consequences of high N_2 and D_2 concentrations in the cover gas.

17. D_2 concentrations of between 2% and 4% in the cover gas require action on the part of the station staff. State 8 typical actions that might be taken.

18. Describe actions that will be taken by control room staff is D_2 concentrations of greater than 4% are indicated.

19. Explain two methods of ensuring the recombination units are operating correctly.

2.6.4 Poison Addition

20. For each of the following applications explain why poison addition might be required, the likely choice of poison and the reason why that poison is most suitable for the circumstances.

   a) Extended outage

   b) Over fuelling (reactivity shim control)

   c) Prior to initial start-up when unit contains fresh fuel

   d) Start-up after a poison outage.

e) Large increase in power following sustained operation at lower power level

21. State four indications available to the control room operator when adding poison manually.

22. How does one ensure that the proper amount of poison is added when the reactor is critical?

23. How does one ensure that the required amount of poison is added during an extended outage or a guaranteed shutdown?

24. Why is there an automatic gadolinium addition feature?

25. State two reasons why poison unavailability is a concern?

26. What is the main concern for inadvertently removing poison during start-up operation?

27. State one concern for inadvertently removing poison during full power operation.

28. What are two main consequences of using boron poison when gadolinium is preferred?

29. State 3 consequences of inadvertent poison addition during full power operation:

2.6.5 Moderator Purification

30. State three reasons for keeping moderator water pure.

31. State three ways moderator water purity is maintained.

32. How the rate of gadolinium removal controlled?

33. Why is a multistage technique required for boron removal?

34. Why should boron or gadolinium be removed when their reactivity effects are no longer required?

35. How is purification flow maintained?

36. What are two consequences of high purification flow?

37. What is the consequence of low purification flow?

38. How is the ion exchange inlet temperature maintained?

39. What are three consequences of a high purification inlet temperature?

40. What is the consequence of high differential pressure across a purification system component?

41. How is low conductivity maintained?

42. What is the consequence of continued use of spent resin for purification?

43. How would control staff know if a boron-saturated IX column had been inadvertently valved in?

44. What is the consequence of resin escape into the main moderator system?

45. Why must the moderator purification be isolated during the overpoisoned guaranteed shutdown state?

3 Heat Transport System

3.1 HTS Heat Sources & Heat Transfer Paths

The main purpose of the Heat Transport System (HTS), i.e. to transport the heat produced in the fission process to the steam generators by means of pressurized D_2O. There are three basic formats of heat transport systems used in current CANDU reactors. These are:

46. Double loop, with counter flow through the reactor, and pressure control by feed and bleed

47. Double loop, with counter flow through the reactor, and pressure control by means of a pressurizer

48. Single loop, with counter flow through the reactor, and pressure control by pressurizer.

An additional function of the Heat Transport System (HTS) is to provide a barrier to the release of radioactivity to the environment. In the reactor zirconium alloy pressure tubes are used for neutron economy. The remainder of the system constructed mainly from carbon steel.

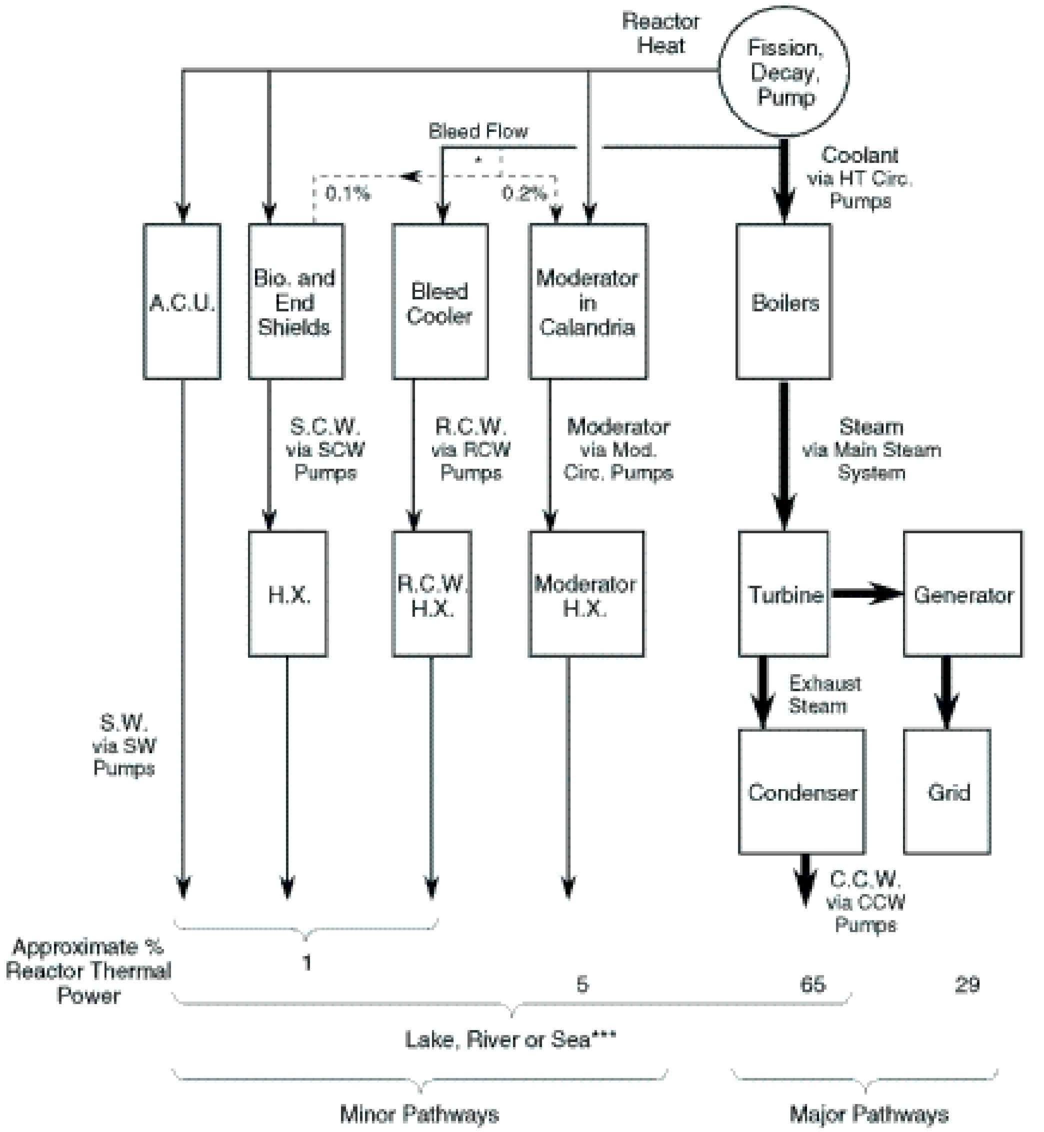
The HTS must have the capability of removing both full power heat from the reactor and the decay heat following a shutdown. In this section we will describe the pathways by which the HTS can remove the full power heat output from the reactor as well as when the unit is forced into the poison prevent mode. The shutdown operational function will be discussed in a later module.

3.1.1 Reactor At Full Power

The approximate division of the heat produced in a CANDU reactor at full power is:

• Heat from the fission process	~ 92-93%
• Heat from the decay of fission products	~ 6-7%
• Heat from the HTS pumps	~ 1%

At full power, the heat from the above sources is transported by the HTS coolant (D_2O) to the boilers where the feedwater inventory, being converted into steam, provides the main intermediate heat sink (Figure 3.1)



Key	
A.C.U. S.W. S.C.W. R.C.W. C.C.W.	Air Cooling Unit Service Water Shielding Cooling Water Recirculated Cooling Water Condenser Cooling Water

* Some channel heat will be transferred to the moderator and end shields by conduction and radiation

*** An additional heat exchange is required for cooling to the sea, ie. Recirculated Cooling Water to Raw Sea Water

Figure 3.1
Full Power Heat Removal Chains- Major and Minor Pathways

Steam produced in the boilers provides the driving force for the turbine generator. About 30% of the energy leaving the boilers will be converted to electrical energy for the grid during normal operation. The remaining 70% of the steam's thermal energy is transferred via the condenser and condenser cooling water (CCW) to the lake, river or sea. This energy (heat) is released as the exhaust steam from the turbine is reconverted to a liquid state.

There are also other pathways for various auxiliary systems, all ultimately ending at the lake (river or sea). As seen in Figure 3.2, most of these pathways do not remove a large amount of heat (minor pathway). The only significant minor pathway auxiliary system is that for the moderator, which accounts for approximately 5% of reactor power output. Recall that this heat is generated by a combination of thermalizing neutrons and absorbing gamma rays from fission, fission products, and activated core components.

Note that these minor heat paths will not be shown in subsequent diagrams although you should assume that they are still available for heat removal unless otherwise specifically stated.

The various shield systems at different locations (End and Biological/Thermal) have been lumped into a single category.

The circulation of the various heat transport mediums, such as Condenser Cooling Water (CCW), Recirculated Cooling Water (RCW), etc., requires the operation of circulating pumps for the overall heat transport mechanism to remain viable. The heat transfer diagrams shown in this module, and subsequent modules, will assume the correct (normal) operation of various pumping sources.

3.1.2 Poison Prevent Mode

This mode of operation is especially useful when steam flow to the turbine is lost with the reactor at power (eg, on a turbine or generator trip), and the prospects are good for returning the turbine generator to service within a few hours. As an alternative to a unit outage, this mode is used to prevent the reactor from poisoning out due to higher than normal xenon levels.

Clearly the steam must be discharged elsewhere in order to keep the boiler heat output via the steam equal to the heat input from the coolant (Fig. 3.2). At some stations, the steam is discharged to atmosphere via Steam Reject Valves (SRVs); at other locations, the steam is discharged directly to the condenser via Condenser Steam Discharge (Dump) Valves (CSDVs). The SRVs are rated for 100% full power and CSDVs are rated for 75-100% full power. A portion of the steam flow is directed to the deaerator to maintain deaerator pressure and feedwater temperature by replacing the extraction steam normally used.

Ideally reactor power could be maintained at full power to be absolutely certain that a poison outage does not occur. In practice, reactor power, hence steam flow, is maintained at the minimum - about 60% to 70% - at which the Xe transient can be overridden using reactivity devices as required. The reasons for operating at reduced power are as follows:

1. At stations using SRVs: to conserve feedwater, which is being lost to the atmosphere.
2. At stations using CSDVs and having condensers with limited thermal capacity: to avoid overloading the condenser and excessive piping vibrations (note that some stations have condensers with 100% full power capacity).
3. Economic savings due to lower fuel and fuelling costs.

Figure 3.2 a) depicts the Poison Prevent heat transfer chain for stations using SRVs. The coolant transports fuel and pump heat to the boiler, and steam transports the heat from the boiler to the atmosphere via the SRVs.

Figure 3.2 b) depicts the corresponding process at other stations. Steam transports the heat from the boiler to the condenser via the CSDVs and the CCW transports the heat from the condenser to the lake, river or sea, depending on the station.

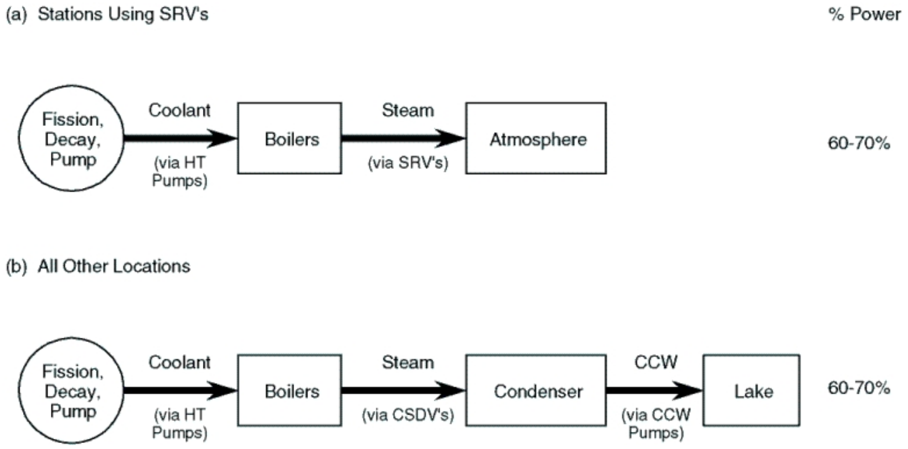


Figure 3.2
Poison Prevent Mode Heat Removal Chain

3.1.3 Delayed Hydride Cracking

The movement between various reactor-operating states is carefully controlled and is detailed in the various station operating manuals. One general constraint imposed on HT system operation between states is concerned with Delayed Hydride Cracking (DHC).

In this course we will address the general methods adopted to minimize the onset of DHC in the pressure tubes. Experience indicates that the problem is essentially temperature/stress related. The highest risk is present when HTS temperatures are in the area of ~100-200°C. Operating procedures are, therefore, designed to avoid operation in this area and also to pass through this temperature band as quickly as possible (and in a continuous manner) both during heatup and cooldown of the unit. To further limit stress levels, this transition may also occur at pressures lower than normal operating pressure.

3.1.4 Hazards

The heat transport system is normally operated at high temperature and pressure and, therefore, has all the conventional hazards due to these effects.

In addition there are radiation hazards generated as a result of reactor operation. These include both activation and fission products. These materials are then distributed throughout the system resulting in:

a) Contaminated D_2O containing:

  - i) tritium
  - ii) Fission products as a result of any fuel failures or tramp uranium on fuel bundles (from manufacturing process);
  - iii) Activation products.

b) Contaminated surfaces due to:

  - i) Plating out of activation products;
  - ii) Crud deposits
  - iii) Collection in IX columns and filters

Contaminated D_2O is a significant hazard when leaks or spills occur, when the system is opened, or when adding or removing coolant.

Contaminated surfaces are hazardous when working with an open, drained system or during component maintenance.

In addition, when at power, there is a danger of elevated gamma and neutron fields around the system components (due to N^{16} and O^{19}).

3.1.5 Hydrogen Hazards When Cold

The necessary addition of hydrogen gas to the system when operating can cause two major problems when the system is cold and depressurized:

a) Hydrogen embrittlement of the zirconium alloy components.

b) Hydrogen-related explosion hazards as the hydrogen comes out of solution following system depressurization. This is of particular concern if the system is to be opened for repairs. This is why the hydrogen addition system is isolated before the unit is depressurized during a shutdown. Purging may be required particularly if welding operations are to be undertaken.

These two problems require that H_2 additions to the HTS be limited to that level required to maintain the system specifications.

3.1.6 Summary Of The Key Concepts

- The two major heat removal pathways at full power are power output to grid and rejection of heat to the lake (river or sea).

- For poison-prevent operation the major heat removal path is via the steam rejected directly to the condenser or to the atmosphere.

- The general operational method to combat DHC in pressure tube components is to avoid operation with the HTS in the temperature range 100°C-200°C and pass through this range quickly and continuously when required to do so.

- The HTS has potential hazards from both conventional and radiological sources.

- H_2 increases the risk of hydrogen embrittlement of zirconium alloy components when the HTS is cold, H_2 poses an explosion hazard as it comes out of solution when the HTS is cold and depressurized.

3.2 HTS Pressure & Inventory Control

The primary role of the Heat Transport System (HTS) is to transport the heat generated by fission and decay heat from the reactor to the boilers, which produce steam to run the turbine generator.

The turbine requires saturated steam at a pressure of approximately 4.5 MPa. If the HT system is to remain subcooled, ie, a liquid, this means that the HTS must also be a pressurized system. Also, taking into account the ΔT required to transfer heat from the HT system to the boilers, the HTS has to be pressurized to approximately 9 to 10 MPa.

These high pressures dictate the need for a pressure control system with operating requirements which must satisfy both mechanical and nuclear concerns.

3.2.1 Pressure Control

Mechanical Concerns

The HT system is a pressure boundary and must remain intact. Operating at a higher pressure than normal in the HT system increases the likelihood of a rupture of the HT system and thus, a Loss of Coolant Accident (LOCA). A LOCA results in a loss of coolant inventory, which may also result in insufficient coolant being available to cool the fuel.

Nuclear Concerns

On the other hand, operating at too low a pressure in the system will result in excessive boiling. This inevitably would lead to fuel overheating either as a direct result of film boiling (dryout) or through loss of coolant flow in the channels caused by pump cavitation. In addition, due to the positive void coefficient, channel voiding leads to large increases in reactor power output, which will tend to further promote boiling and fuel overheating if no protective action is taken. Note that excessive boiling, resulting in fuel overheating and voiding, can also occur at normal system pressures with blocked or restricted coolant passages.

Note that this requirement, i.e. to avoid excessive boiling, still allows for the HTS, at most stations, to be operated at high power with a limited amount of boiling (nucleate boiling) occurring at the exits of some channels. Typically, in a number of channels, 3-5% boiling occurs. This improves heat transfer from the fuel and adds to the extractable heat available to the boilers.

Even at stations where limited boiling occurs at full power, it ceases once the reactor power output falls to ~<90% FP.

Given a totally enclosed heat transport system, pressure will vary directly with the average temperature of the HTS. Coolant pressure increases due to swell as the average temperature increases during reactor power increases. Conversely, pressure decreases as a result of coolant shrinkage during power reductions.

Coolant swell and shrink are major phenomena. A typical unit's HTS swell may be as much as 60 m^3 on warmup with an additional 10 to 20 m^3 as power is raised from 0 to 100% full power. Given the incompressible nature of the coolant, the addition of even 1 m^3 of coolant to a non-boiling pressurized heat transport system would increase pressure significantly.

These conditions dictate the need for HTS pressure and inventory control system. This system ensures that there is adequate coolant at the correct conditions to remove the heat from the fuel.

3.2.2 Heat Transport Pressure Control

In the previous module we discussed the normal operational states of the HTS. Recall that it is necessary for the HTS pressure to be controlled at all power levels - from a cold shutdown condition to 100% Full Power.

We have already mentioned in this module, the volume of D_2O inventory changes which occur as the unit is maneuvered between 0% full power cold and 100% full power hot and vice versa. It was also stated that the major inventory change occurred on warmup of the unit to about 250°C (approximately three times that change which occurs between 0% and 100% FP).

This latter fact is the reason why two methods of pressure control are required on most CANDU reactors, depending on the power level of the reactor. These two pressure control methods are known as solid mode and normal mode.

Solid Mode Pressure Control

Solid mode describes the pressure control of the HTS while the pressurizer is isolated (in stations using pressurizers). In this mode, pressure control is by feed and bleed action, ie, inventory addition and removal. The significance of the word solid is that no compressible vapour space exists within the system to cushion pressure transients (the system is totally non-boiling and the pressurizer is isolated).

With the HTS pressure at its setpoint. neither feed nor bleed action is required, If pressure rises above the setpoint, bleed action will remove inventory from the HTS and lower the pressure. Should pressure fall below the setpoint, the opposite occurs, ie, feed valve opens and inventory is added to the HTS (refer to Figure 3.3 for a simplified feed and bleed controller)

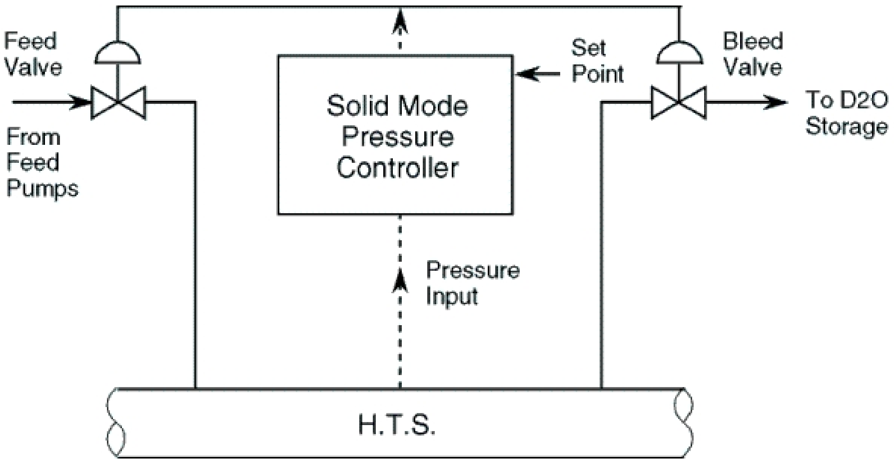


Figure 3.3
Simplified Feed and Bleed Controller

Note that during unit warmup, the bleed valve will be at or near the fully open condition to remove the swelling D_2O from the HTS. On unit cool down, the opposite will occur, ie, the feed valve will be open fully.

In practice, it is desirable to have a percentage of the HTS D_2O circulated through the purification system to remove crud, fission products, and impurities. The bleed valve is biased open a small amount to achieve this (except for CANDU 600, which is discussed later in the module). This will result in a drop in system pressure so the controller will open the feed valve to maintain system pressure at setpoint.

During solid mode operation, the feed and bleed system, in addition to the above, performs the following functions:

a) It supplies D_2O to the Pump Gland Seal Cooling System.

b) The bleed condenser (or degasser condenser in some stations) accepts coolant discharge from the HTS (bleed valves, HT relief valves, steam bleed valves, pressurizer relief valves depending on the station). This ensures that this coolant is available for use when required.

During solid mode operation, the pressurizer is isolated from the HTS by a motorized valve. At this time, saturation conditions are established in the pressurizer at normal operating pressure by manipulation of the electric heaters and steam bleed valves (in preparation for valving in to the HT system).

Normal Mode Pressure Control

Normal mode control is selected during normal operation. In this mode, the pressurizer is no longer isolated and the pressurizer (sometimes called the surge tank) controls HTS pressure.

The pressurizer is shown in Figure 3.4. It is connected to the HTS, at a reactor outlet header, by means of a large diameter pipe.

Steam pressure in the vapour space above the liquid is regulated to control heat transport system pressure.

To increase HT system pressure, the steam pressure must be increased. This is achieved by switching on the electric heaters, thus increasing the temperature of water in the pressurizer. This causes the saturation temperature, and hence pressure to increase.

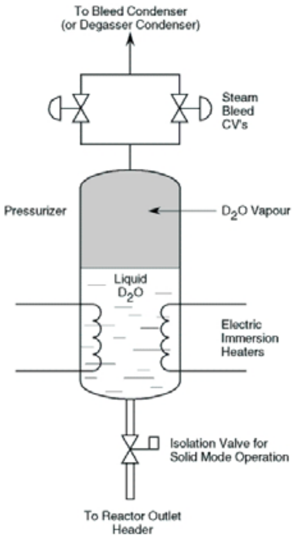


Figure 3.4 - Typical Pressurizer

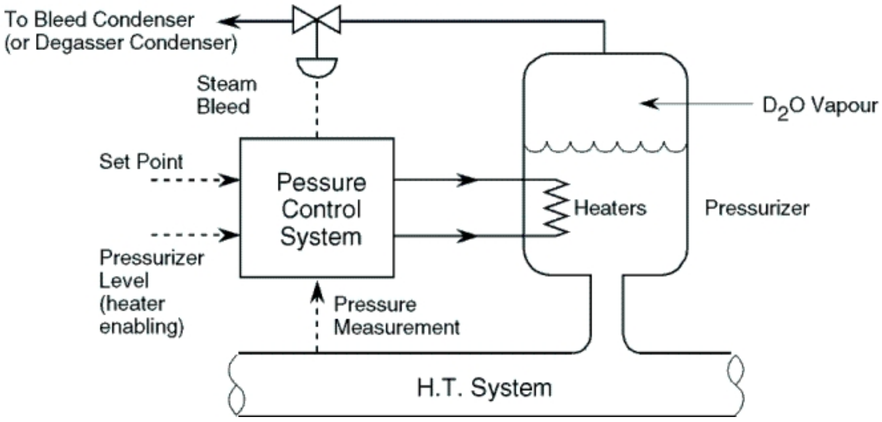


Figure 3.5
HTS Pressure Control (Normal Mode)

To reduce HT pressure, steam is discharged from the pressurizer's vapour space to the bleed condenser (or degasser condenser in some stations) via the steam bleed valves. This causes the saturation temperature and pressure to decrease. The control system is shown in Figure 3.5.

During normal mode operation, the feed and bleed system doesn't control HTS pressure, but performs the following functions.

a) It adjusts coolant inventory to maintain pressurizer D_2O level at its setpoint (see following section on level control);

b) It returns D_2O to the system (via feed) to make up for losses via steam bleed valves (or degas flow in some stations);

c) It supplies cool D_2O to the purification system in most stations;

d) It supplies D_2O to the pump gland seal system;

e) The bleed condenser (or degasser condenser in some stations) accepts coolant discharge from the HTS (bleed valves, HT relief valves, steam bleed valves, pressurizer relief valves, depending on the station). This ensures that this coolant is available for use when required.

Note that functions (c), (d) and (e) are carried out by the Feed and Bleed system in either control mode.

One of the major advantages of pressurizer control is that it provides a faster control in response to HTS pressure transients than a feed and bleed system, (i.e., Large quantities of coolant can be quickly transferred to/from the pressurizer through the large diameter connection to the HTS. By comparison a feed and bleed system will have a more limited capacity.).

Pressure Control Totally by Feed and Bleed

The HTS used at some stations is non-boiling and solid. Pressure control in these situations, at all power states, is by feed and bleed control (ie: inventory transfer). Basically, this is the same as solid mode control at other locations. The feed and bleed system may also provide a D_2O supply for the fuelling machines.

However, in this case the pressure control function is divided into two ranges, termed wide and narrow range.

The wide range covers the warmup and cooldown of the system when the pressure can range from full working pressure to a much lower pressure, ie, control uses a low gain, resulting in coarse control - Wide Range.

For normal full power operation, when tight control about the setpoint is required, control is switched to a higher gain, resulting in a finer control - Narrow Range. More details of this control system will be presented in Instrumentation and Control courses.

Summary Of The Key Concepts

- HT pressures that are too high can cause HTS ruptures (LOCA). Low HTS pressure will result in fuel overheating due to film boiling, and/or loss of coolant circulation due to pump cavitation. Voiding will promote fuel overheating because it introduces positive reactivity, thereby increasing heat production in the fuel.

- Fuel overheating due to film boiling is also possible at full system pressure if a coolant blockage or restriction exists.

- Pressure control is required since the pressure in the HTS varies directly with the HTS average temperature. Inventory control is required because of coolant shrink and swell as the HTS temperature varies.

- For units with pressurizers, the feed and bleed system controls HTS pressure in solid mode. It also provides purification flow (in most stations) and D2O to the HTS pump glands. The bleed condenser (or degasser condenser in some stations) accepts D_2O from the HTS relief valves to prevent the loss of this coolant.

- For units with pressurizers, the feed and bleed system controls pressurizer level in normal mode. It also provides make-up for losses, purification flow (in most stations), D_2O to the HTS pump glands, and maintains the bleed condenser (or degasser condenser in some stations) as a pressure relief vessel.

- For units without pressurizers, the feed and bleed system controls HTS pressure. It also provides the same functions as it does in solid mode in units with pressurizers. It may also provide a D_2O supply for the fuelling machines.

3.2.3 Pressurizer Level Control

Level Control of D_2O in the pressurizer is important for the following reasons:

a) It prevents the uncovering of the electric heaters (on low level) therefore reducing the risk of burning out the heating elements (automatically switched off on low level). This results in the loss of pressure control (ie: cannot increase pressure without the heaters)

b) It prevents the system from going solid as a result of too high a level. Loss of the vapour space results in loss of pressure control

c) Taking account of the limits imposed by (a) and (b) maintains a maximum HTS inventory.

An additional function carried out by the level controller is to ramp up level in the pressurizer as reactor power is increased. This means that shrink or swell as a result of power maneuvers can be accommodated directly by transfer to and from the pressurizer with minimal resort to feed or bleed action. A simplified control system is shown in Figure 3.6.

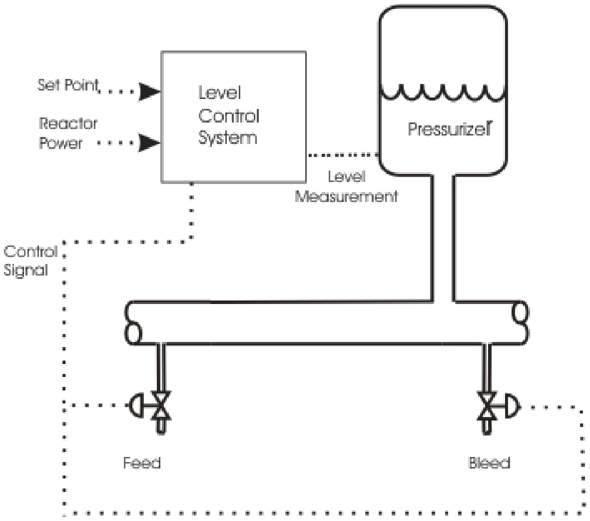


Figure 3.6

Pressurizer Level Control

Similar to boiler level changes with reactor power, the level is at its lowest at low power. This is because the HT inventory will swell as reactor power increases. The low level leaves room for the excess coolant that will enter the pressurizer. The requirement to make up shrinkage while at low power is a minimum, hence a lower level is not a major operating concern. On the other hand, the level is highest at full power. This takes into account the shrinkage that could occur if power is reduced. While at full power, the risk of further swell is minimal; hence the higher level in the pressurizer is not a major operating concern.

Pressurizer level is controlled by use of the feed and bleed valves.

For example, on a power increase, the pressurizer level setpoint will be ramped upwards. The swell, as a result of the power increase, will be accommodated within the pressurizer and will satisfy the increased level requirement. feed and bleed system action will be minimized to adjust HTS inventory. The opposite is true for a reduction in reactor power. The HTS shrink will be supplied from the pressurizer.

An additional advantage, achieved by ramping pressurizer level upwards as power increases, is that, should a reactor trip occur, the resultant shrink in the HTS can be replenished quickly from the pressurizer. Note that it is not practical to provide a pressurizer that is sufficiently large enough to accommodate all swell from 0% power cold to 100% full power hot. It does, however, handle the inventory changes that occur in the on-power condition (zero power hot to full power), with minimum recourse to feed and bleed action. The inventory transfer between cold pressurized and zero power hot, to accommodate shrink and swell, is via the feed and bleed system and D_2O storage tank inventory.

Another advantage of the use of a pressurizer is that it results in addition/removal of inventory at HTS operating temperature directly to/from the pressurizer during transients. This minimizes heat losses and thermal stresses as compared to a solid system (ie, where inventory is cooled as it leaves the system and heated as it returns to the system via the bleed/feed path).

3.2.4 Response of Feed and Bleed to Power Changes

For fine control using feed and bleed, and at the high working pressures used in the HTS, fairly small sized valves are used. Inventory transfer rates, and thus control of pressure transients, are limited.

At stations without pressurizers, using the following techniques reduces the demands on the feed and bleed system:

a) Operating the station (for the maximum possible time) as a base load unit, thus reducing the need for power maneuvers and resulting changes in HTS temperature, and therefore pressure changes.

b) Maintaining HTS average temperature essentially constant in the at-power condition. This is achieved by ramping down boiler pressure, and therefore boiler temperature, as reactor power is increased. Boiler temperature and reactor inlet temperature can be assumed equal, since there should be little ΔT between the HT D_2O at the boiler outlet and the boiler temperature. Thus, as reactor outlet temperature increases (with an increase in reactor power) reactor inlet temperature, under the same conditions, will decrease. The average HTS temperature, ie, the mean of the inlet and outlet temperatures, will remain essentially constant over the power range. System shrink and swell, and therefore feed and bleed requirements, are thus minimized. This effect is shown in Figure 3.7.

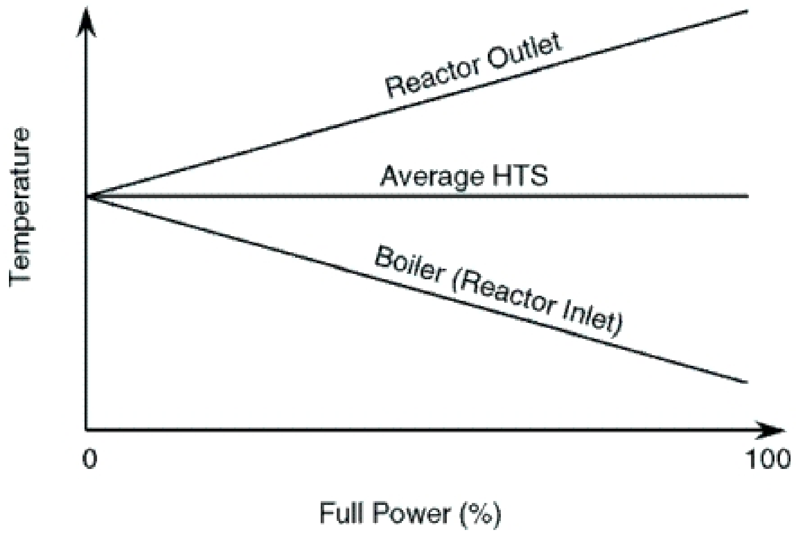


Figure 3.7 - Reactor, Boiler and HTS Temperature Trends

The inventory transfer between cold pressurized and zero power hot, to accommodate shrink and swell, is via the feed and bleed system and D_2O storage tank inventory.

3.2.5 D_2O Transfer And Storage

D_2O Transfer System (Interunit Tie)

At a typical CANDU generating station (single or multi-unit), provision must be made to ensure that sufficient quantity and quality of D_2O is available for extended, and safe unit operation.

Each station (multi-unit) has a central D_2O storage facility to receive shipments of D_2O from the manufacturing plants. It can be pumped from this central location to the reactor systems as required. This facility is also capable of holding the D_2O from one moderator or one HTS, should a reactor system require draining.

This central supply and distribution system reduces handling of D_2O drums and, therefore, reduces personal exposure to tritium from any spills that may occur. It is also a faster method of transferring D_2O. It also allows transfer of D_2O between units.

Separate storage is supplied for any downgraded D_2O that may have escaped or have been removed from the reactor systems. This is the usual source of D_2O for the station upgrading facility. Since HTS D_2O has a lower tritium content than the moderator, separate storage is provided for each system.

D_2O Storage Tanks

Each unit's HTS has its own individual D_2O storage tank. Its purposes are to:

a) Provide enclosed storage for D_2O to makeup leakage form the HTS.

b) Accommodate system D_2O shrink and swell during reactor power maneuvers.

c) Provide a positive suction head to the HTS feed (pressurizing) pumps.

As indicated in (b) above, the storage tank level will vary with reactor operating state.

It is important to maintain a minimum level in order to ensure adequate feed pump suction head, and to provide an inventory to cover expected normal operation, Too high a level at low power may result in the tank being completely filled by the swell as power increases. The tank forms part of the sealed HTS system, even though at a lower pressure (typically 10-20 kPa(g)). The vapour space above the D_2O is filled with helium and providing both a non-corrosive, non-explosive atmosphere with the ability to remove any D_2 (produced by radiolysis) by purging. This space would be lost on very high level, allowing this tank to pressurize. Any overpressure is relieved initially by valving to the recovery/collection system. Extreme overpressure protection is provided by a rupture disc, which will discharge excess coolant to containment.

Summary Of The Key Concepts

- Low pressurizer level could result in exposing the electric heaters to the steam causing burnout. Also the level must be maximized to ensure that there is sufficient inventory for rapid shrinkage make-up. High pressurizer level could cause the pressurizer to go solid, hence losing pressure control.

- Pressurizer level is ramped with power changes to accommodate shrink and swell and to minimize feed and bleed requirements.

- Feed and bleed requirements are minimized for systems without pressurizers by ramping down boiler pressure as reactor power is increased. This maintains HTS average temperature constant to minimize swell. To further help, these units are run as base load units.

- The feed and bleed system provides the inventory transfer between the cold pressurized state and zero power hot conditions.

- The purpose of the inter-unit D_2O tie is to centrally store and distribute D_2O and allows transfers of D_2O between units.

- The purpose of the D_2O storage tank is to provide D_2O for loss make-up, accommodate shrink and swell and provide a positive suction head to the feed pumps. A minimum level must be maintained to make-up D_2O for losses and to ensure adequate suction head at the feed pump. A high level could cause the tank to go solid resulting in loss of coolant to collection/recovery or to containment through the rupture disc.

3.2.6 Bleed From The System

We have already mentioned that a portion of the HTS inventory is diverted from the system on a continuous basis, and put through a purification process.

This clean up will be performed by a combination of filters, ion exchange columns and strainers. Ion exchange resins are generally not able to tolerate excessive temperatures. Temperatures greater than ~60°C may cause resin efficiency to decrease and perhaps cause resin breakdown with the release of, typically, fluorides and chlorides. These ions can promote stress corrosion cracking in the zirconium and stainless steel components of the HTS. In some stations purification is performed at full system pressure, at other stations it is performed at a reduced pressure.

The purified D_2O is either returned to the HT system or it can be held in the D_2O storage tank at nearly atmospheric pressure and cooled (as previously mentioned). This tank is maintained at a pressure close to atmospheric. It also accommodates the excess D_2O due to swell on a unit warm up from a cold state (the D_2O transfer and storage system is used, as required, to maintain the D_2O storage tank level in the correct range).

Therefore, for storage at all stations and purification at most stations, it is necessary to both cool and depressurize any bleed from the HTS. This is accomplished differently at different locations, but there are two basic methods described below.

3.2.7 Bleed/Purification Using Bleed Condensers

A representative pressure and inventory control/purification system is shown in Figure 3.8.

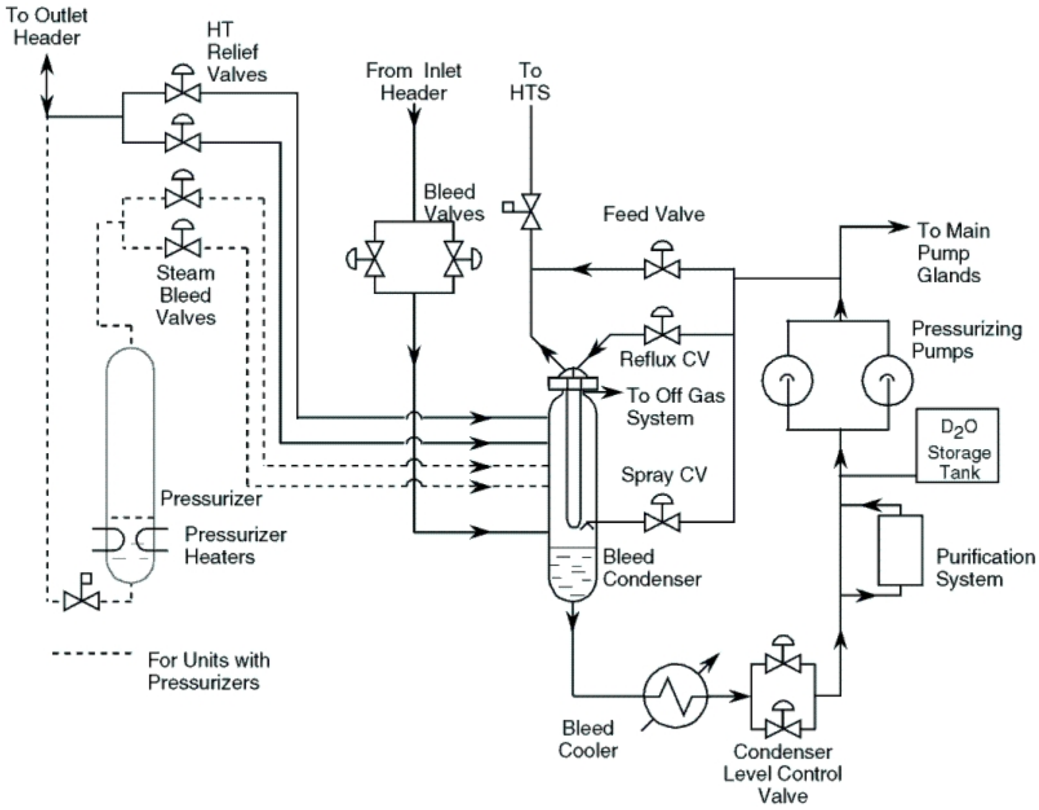


Figure 3.8
Heat Transport Pressure Control for Systems Using Bleed Condensers

The bleed condenser has two major roles:

a) To reduce the pressure and temperature of any bleed from the HTS from approximately 9-10 MPa and ~300°C (8 MPa and 250°C at some stations) to 2 MPa and ~200°C.

b) To accommodate any discharge of D_2O from the HTS. This can be in either liquid (via the HT pressure relief valves) or vapour (from the pressurizer via the steam bleed valves).

The bleed condenser will, as its name implies, condense any bleed flow from the HTS. There are two methods of achieving this condensing action:

Reflux Cooling

a) This is achieved by taking a flow of already cooled and purified D_2O which is being recirculated or returned to the HTS by the pressurizing (feed) pumps and passing it through a tube bundle located in the bleed condenser. As well as condensing the steam, this heats the D_2O that is returning to the HTS, thus efficiently recovering this heat.

Spray Cooling

b) This is achieved by spraying cooled D_2O into direct contact with the incoming bleed flow (note the bleed flow will flash to steam as it encounters the lower pressure of the bleed condenser).

Spray cooling is used as a backup to reflux cooling, should reflux cooling not be able to maintain the process at its required setpoint. If the reflux flow is at a maximum and pressure continues to increase in the condenser, spraying will commence. This direct contact method of condensing should quickly lower pressure but at the expense of mixing already cooled and purified D_2O with that yet to be treated. This places a heavier load on the purification circuit. Spray cooling would also likely add to degassing of the coolant in the bleed condenser. This will result in the impairment of reflux cooling. This will also lead to level control problems in the bleed condenser, since the incoming bleed will be at a high rate, with spray cooling adding to the inventory.

The D_2O leaving the bleed condenser will be at a pressure of approximately 2.0 MPa and a temperature of about 200°C.

Further cooling to less than 50°C, required before passing to the ion exchange columns, is performed by the bleed cooler.

Electric immersion heaters can be used to establish the initial saturation conditions in the bleed condenser (only at some stations). In others the relatively war water expelled from the HTS to the D_2O storage tank provide the energy to warm the bleed condenser. Relief valves are necessary to provide pressure relief for the bleed condenser, when the level rises enough to cause the bleed condenser to go solid. The bleed condenser relief valves discharge to recovery sumps (or tanks in some stations) within containment. (These components are not shown in Figure 3.8).

3.2.8 Bleed/Purification Using A Degassing Condenser

A representative pressure and inventory/purification circuit using a degassing condenser is shown in Figure 3.9

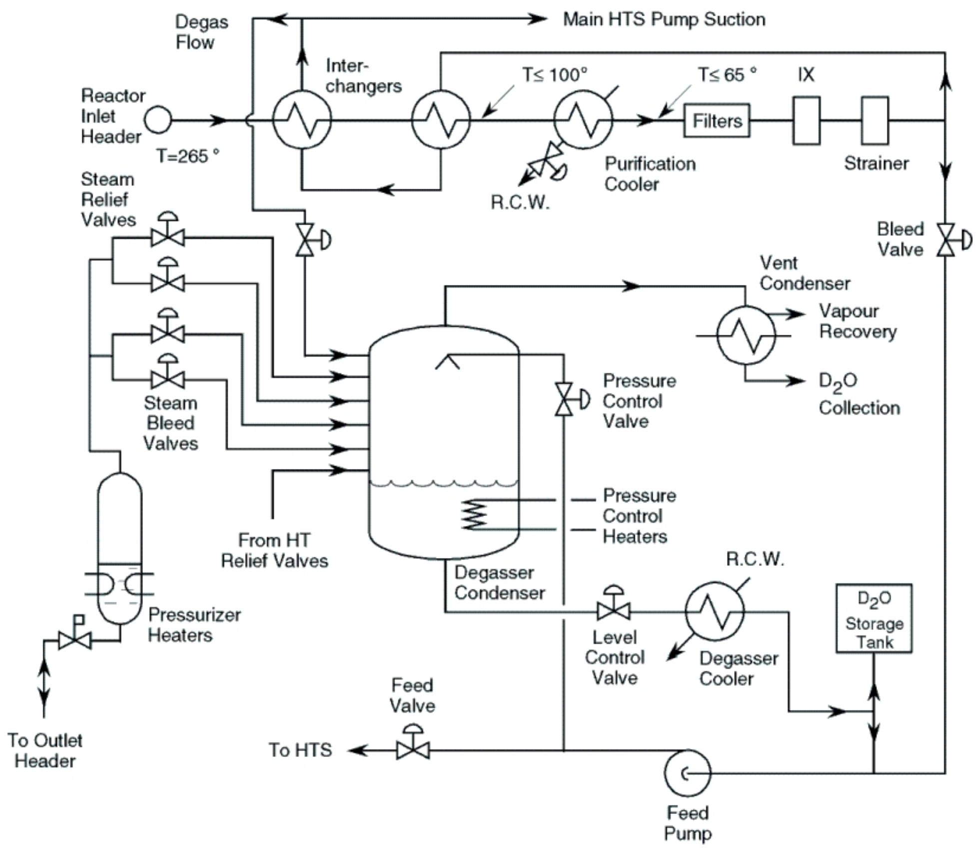


Figure 3.9
600 MW Bleed, Purification, Pressurizing and Degassing Systems

Note that purification in this type of arrangement is conducted at full system pressure. Because the HT Pumps drive this purification flow, it is independent of the bleed circuit. Hence bleed flows can be quite small during system operation. This type of purification will be discussed in more detail in a later module of this course.

For this system the degassing condenser has the following major roles:

a) To accommodate any discharge of D_2O from the HTS. This can be in either liquid (via the HT pressure relief valves) or vapour (from the pressurizer via the steam bleed or steam relief valves).

b) To reduce the pressure and temperature of any flows from the HTS from approximately 9-10 MPa and ~300°C to 1.2 MPa and ~190°C.

c) To degas flows from the HTS. This degassing function will be discussed in a later module of this course.

The degasser condenser will condense flow from the HTS by spraying cooled D_2O into direct contact with the incoming flows (which will flash to steam as it encounters the lower pressure of the degassing condenser).

Further cooling to less than 70°C (typically $\leq$ 30°C) will be performed by the degassing cooler before the D_2O is returned to the HTS or D_2O storage tank. This further cooling is required because high temperatures at this point would cause net positive suction head problems at the feed pump. Note there is no temperature control on the degasser cooler (other than the high temperature over-ride on the level control valves). The recirculating cooling water is always at a maximum flow rate to ensure maximum cooling.

Note that the electric immersion heaters can be used to maintain the conditions in the degasser condenser for degassing (when steam bleed flows are insufficient to maintain pressure). Just like the bleed condenser, relief valves are necessary to provide pressure relief for the degasser condenser when the level rises enough to cause the degasser condenser to go solid (these are not shown in Figure 3.9). The degasser condenser relief valves discharge in to recovery sumps within containment.

3.2.9 Power Maneuvers

Figures 3.8 and 3.9 show, in a very simple format, two types of pressurizer systems and a feed and bleed system fitted to CANDU units. We can use these diagrams to explain how the different systems will respond to normal power maneuvres (between 0% and 100 FP) and a limited number of system upsets.

Pressurizer System

As mentioned previously, an increase in reactor power raises average HTS temperature. This causes a corresponding coolant swell causing an increase in pressure. The increase in pressure and inventory will cause:

a) Additional D_2O inventory to enter the pressurizer,

b) The steam space above the liquid in the pressurizer to be further compressed

Effect (b) will be countered by the control system opening the steam bleed valves in the pressurizer until pressure is once again at the setpoint.

Since pressurizer level setpoint is ramped upwards as reactor power increases, the inventory transferred to the pressurizer will provide the extra D_2O required to bring the level to its new setpoint. Any discrepancy will be made up with bleed valve opening.

The steam discharged to the bleed condenser, plus any additional bleed flow input, will cause pressure and level in the bleed condenser to increase. In the case of the degasser condenser, the steam discharge and any additional degassing flow will similarly cause its pressure and level to rise.

Pressure will be returned to setpoint by some additional reflux flow while the bleed condenser input is at its increased level. Spray action is not likely to occur for a normal power maneuver. For the degasser condenser case, the pressure reduction will be performed by spray cooling.

The increase in bleed condenser/degasser condenser level will be removed by an increased opening of the level control valves.

The additional outflow from the bleed condenser/degasser condenser will increase the loading on the bleed/degasser cooler. In the case of the bleed cooler, additional cooling water flow will be required to maintain the temperature at its setpoint. For the degasser condenser, the temperature at the degasser cooler outlet will increase slightly as the thermal load increases (recall that RCW valves are always fully open).

Once the new steady state power has been established, it is probably that reflux, level and cooling water control valves (if any) will return to their pre-manoeuvre positions.

On a large power reduction, HTS coolant shrink will result in a decrease in pressurizer level and a slight pressure reduction in the pressurizer steam space. Pressurizer heaters will come on to restore system pressure to setpoint.

Feed and Bleed System

For a feed and bleed system, an increase in reactor power output will cause a new, lower boiler pressure setpoint to be generated. Recall that this is intended to keep the average heat transport system temperature relatively constant during normal power maneuvering. However, the range of boiler pressure adjustment is limited to achieve reasonable thickness of boiler vessels (high pressure limit) and maintain high thermal efficiency of the cycle (low pressure limit).

Because of these limitations, average heat transport system temperature will increase slightly during reactor loading. Therefore, HTS pressure will also increase. Opening the bleed valve will be necessary to reduce pressure to the setpoint.

The additional bleed flow will bring about a similar response (as discussed earlier in the pressurizer section) from bleed condenser pressure and level controllers and bleed cooler temperature controller.

Note that for a reduction in power, an opposite response will occur, HTS average temperature will reduce, resulting in a drop in HTS pressure. This pressure decrease will require feed action to restore pressure to the setpoint.

Bleed action will reduce, resulting in the less reflux flow to prevent bleed condenser pressure falling. Outflow from the bleed condenser will be reduced to maintain level. This in turn will reduce loading on the bleed cooler.

3.2.10 Summary Of The Key Concepts

- Bleed condenser pressure is controlled by condensing D_2O by reflux cooling and spray cooling. Spray cooling is used as a backup since it increases load on the purification circuit and creates level control problems. For stations using a degasser condenser, cooling is by spray cooling only.

- As reactor power increases, pressurizer systems will respond as follows:

    - HTS temperature increases, causing swell and an increase in HTS pressure,

    - Steam bleed valves open to reduce HTS pressure,

    - Pressurizer level increases due to swell (level setpoint is also ramped up),

    - Bleed condenser (or degasser condenser) level increases and load on the bleed (or degasser) cooler increases,

    - Bleed system action should be minimized.

- As reactor power increases, for a feed and bleed system (no pressurizer), response will be as follows:
    - Boiler pressure is ramped downward to maintain HTS average temperature constant, hence HTS pressure increase is minimized,
    - Bleed condenser level increases due to increased bleed flow and load on the bleed cooler increases.

3.2.11 HT Pressure Relief

Pressure relief must be provided to prevent overpressurization with subsequent rupture of components in the HTS.

Rupture of components could result in one or a combination of the following:

1. A HT coolant spill requiring Emergency Coolant Injection if the loss of coolant is large enough (ie: loss of heat transfer medium),
2. Fuel failures due to the decrease in cooling capacity (as a result of voiding in the HTS due to reduced system pressure)
3. A reactor power increase due to an increase in reactivity as a result of the positive voiding coefficient. This situation would require the operation of shutdown systems to reduce power if the Reactor Regulating System (RRS) is not capable of control.

Pressure relief obviously reduces the probability of these undesirable events occurring.

Note that events causing slow HTS swell / pressure increases are not normally of major concern since these events are handled within the capacity of the pressure and inventory control system. On the other hand, rapid pressure increases (beyond the capacity of the pressure and inventory control system), if not counteracted, will cause serious overpressurization.

Overpressurization in the HTS can be caused by:

Mechanical Compression of the Coolant

This could be the result of the pressurizing feed pumps supplying D_2O to the system at a rate above that which pressure and inventory control can accommodate (ie: insufficient bleed for the HTS due to bleed valve malfunction).

In some stations this condition is also possible during refuelling due to overpressurization by the fuelling machine pressurizing pumps. This would only be a concern if the overpressure relief devices on the fuelling machines failed to function.

Coolant Swell Due to Increases in HTS Temperature

If the coolant swell, as a result of an increase in HTS average temperature, cannot be contained by the pressure and inventory control systems, major overpressurization of the HTS can occur.

These events are potentially more hazardous than mechanical over-pressurization, because the levels of over pressure achievable may be very large (ie, greater than the capacity of the relief valves).

Events leading to this type of overpressurization include:

a. Pressurizer heaters failing to turn off at HTS pressure setpoint. The increased boiling in the pressurizer will increase D_2O pressure in the pressurizer. Since the pressurizer and HT system are connected, pressure will also increase in the main HTS.

b. Loss of reactor regulation leading to reactor power increase above normal full power setpoint. Assuming that the heat production rate is greater than the heat removal rate, this results in HTS swell and accompanying pressure rise (protected against by shutdown system trip).

c. Loss of HTS circulating pumps while at power. The loss of coolant flow will result in an immediate increase in HTS average temperature leading to high HTS pressure (again protected against by shutdown system trip - protected by both low HT flow and high HT pressure trips).

d. Conventional (Boiler) System Upsets

i) Cessation of steam flow from boilers due to turbine trip or load rejection. This occurrence is normally countered by providing an alternate heat sink (steam discharge) and by reducing the heat input to the system by means of a reactor stepback or setback. If the remedial measures do not occur, heat removal from the HTS will be impaired, resulting in an increase in HTS average temperature and a corresponding rise in HTS pressure.

ii) Loss or reduction of boiler feedwater and consequent loss of heat sink capability. As heat sink capacity in the boilers reduces. HTS temperature and pressure will increase rapidly. This is mainly due to the loss of the cooling effect from the preheaters (approximately 20% of the heat sink).

3.2.12 Methods of Reducing HTS Pressure

Two basic methods of obtaining pressure reductions exist:, direct & indirect

> Direct pressure reduction refers to methods that are applied directly to the HTS. Indirect methods are secondary effects from actions to control the steam system. By first influencing the steam system, there will be a variation in heat sink capacity, which affects HTS D_2O pressure.

Basically, direct pressure reduction mechanisms can handle HTS over-pressures resulting from both mechanical and HT temperature increases while indirect methods are capable of handling only events resulting from HTS temperature increases. The reason for this limitation is explained later in this section.

Direct Pressure Reduction

HTS pressure, usually measured at the reactor outlet header, is used to initiate the various relief actions. These are shown in Figure 3.10.

HT Pressure Relief Valves

The HT pressure relief valves are the first defence against an uncontrolled pressure rise. There are generally a number of them, mounted in parallel, discharging from the reactor outlet header(s) into the bleed condenser (or in some stations, the degasser condenser). These valves discharge the excess coolant from the HTS thus limiting the over pressure. Although the boiler safety valves must be capable of discharging the steam produced by 100% or greater reactor power output, the HTS relief valves have only a limited discharge capacity.

The reason for this apparent discrepancy is that the HT relief valves are sized to match the over-pressurization capability caused only by mechanical (pump) methods. To provide sufficient relief valve capacity for all likely events would not be desirable, as it would increase the risk of over relief, with excessive loss of inventory. This would lead to saturated conditions being reached in the main HTS and excessive boiling in the HTS. This could lead to steam banketing and fuel overheating. The relief valves may have staggered set points to provide progressive action as HTS pressure increases.

Reactor Power Reductions

If the pressure relief valves are unable to stop the pressure rise, reactor power may be stepped back (step decrease in reactor power; typically 30%). This would result in a rapid coolant shrink with associated rapid drop in HTS pressure. This feature is only available for reactors fitted with control absorbers.

At stations without control absorbers, initial attempts to reduce HTS pressure is by coolant discharge via bleed and pressure relief valves. This will cause a high level in the bleed condenser. This will result in a reactor setback on high bleed condenser level. A setback is a power ramp down which results in a more gradual coolant shrink than that achieved by a stepback, ie, pressure reduction will be slower than that for a stepback.

A pressure rise not terminated by either relief valves or reactor setback/stepback will eventually trip the reactor. This quickly reduces thermal power to decay levels (~ 7% FP) causing a rapid HTS D_2O shrink and pressure reduction.

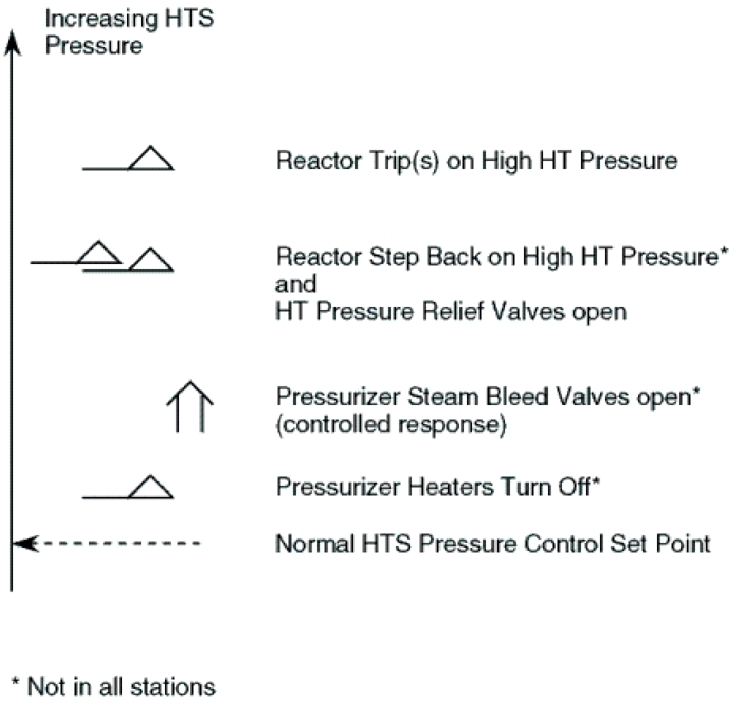


Figure 3.10
Some Direct Methods of HTS Pressure Reduction

Indirect Methods Of Pressure Reduction

Indirect methods act on the steam system to reduce HTS average temperature. This temperature decrease results in coolant shrink. Coolant shrink leads to a decrease in HTS pressure.

The temperature reduction is achieved by lowering boiler pressure (and therefore boiler temperature since the boilers are saturated). The higher ΔT between HTS D_2O and boiler H_2O will result in a higher rate of heat transfer from the HTS and therefore, a reduction in the average HTS D_2O temperature.

Discharging steam from the secondary side lowers boiler pressure; Figure 3.11 illustrates the methods available. A rise in HTS pressure due solely to mechanical over-pressure mechanisms cannot be handled by indirect methods (unless manual intervention is used) and will not, by itself, cause any steam valves to open.

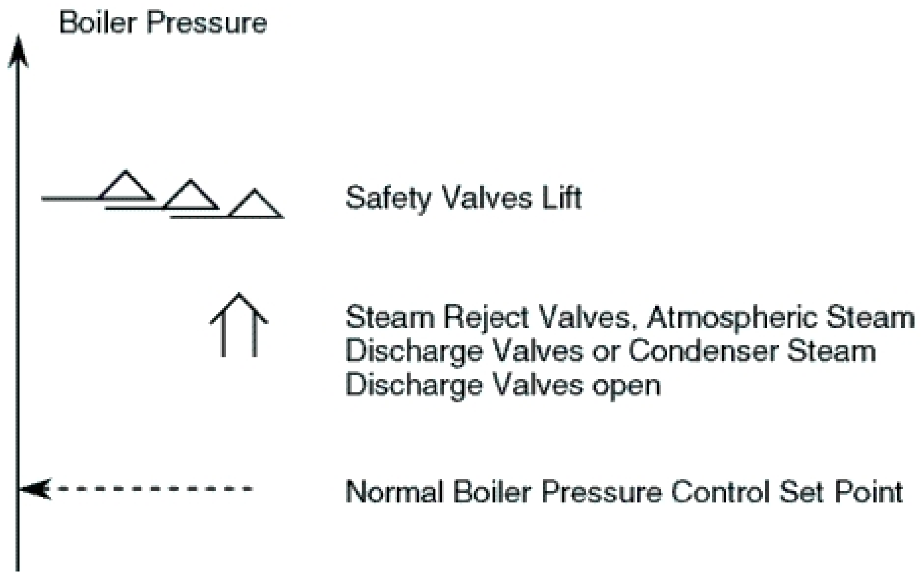


Figure 3.11
Indirect HTS Pressure Reduction Methods

At most stations, atmospheric steam discharge valves and condenser steam discharge valves are used. The other stations use steam reject valves which discharge only to atmosphere. All plants, of course, use safety valves.

Discharging steam (to atmosphere or condenser) merely provides an additional or alternative heat sink to the turbine. If the heat removal provided by steam discharge is equal to power input to the boilers, then no HTS pressure rise will occur.

The steam reject valves at some stations, or the combined atmospheric and condenser steam discharge valves at other stations have at least 75% full power steam capacity. Thus, they are capable of handling fairly large upsets. However, should they prove inadequate to control steam pressure, the steam safety valves (set at higher relief pressures) will provide a further heat sink. The safeties are required by law to be capable of >100% steam power removal (ie, this takes into account reactor trip setpoints and channel power variation [ripple] effects).

Steam rejection can also be used, together with direct methods of pressure reduction, to cope with coolant swell upsets. In such cases, the steam reject valves (SRVs) could be opened manually by the unit operator, Manual SRV opening is a slow response, but the effect is of large capacity. Depending on the station, opening of the SRVs (or ASDVs) may also be used as an initiating parameter for a reactor setback to supplement the pressure reduction by reducing the heat input to the HTS.

Automatic opening of the SRVs could be employed on a HT pressure rise. But due to the time delay [~10 seconds] from steam discharge to HT average temperature change, rapid HT overpressures caused by primary system events could not be controlled automatically by this method. With the reactor shutdown and the heat transport system cold, steam rejection is not capable of assisting relief devices for heat transport mechanical overpressurization, since there will be no steam to discharge.

3.2.13 Summary Of The Key Concepts

- Pressure relief must be provided to prevent damage to the HTS.
- Rapid HTS swells are beyond the capability of the pressure and inventory control system.
- Over pressurization is caused by mechanical compression of the coolant or by coolant swell.
- Direct methods of HTS pressure reduction act directly on the HTS D_2O (ie, relief valves, reactor power reduction causing HTS D_2O shrink).
- HTS pressure relief valves are sized for mechanical overpressure events only. To provide pressure relief capacity for all possible events would increase the risk of over relief yielding excessive inventory loss.

3.2.14 Major Upsets

Failed Open Pressure Relief Valve (PRV)

Should a PRV fail open, coolant is being lost from the system. (In some stations this these relief vales are called liquid relief valves (LRV). Heat transport pressure will fall rapidly and efforts to restore pressure will commence, i.e., pressurizer heaters on (where applicable), feed action to restore inventory.

The flow through the PRV will cause bleed condenser (or degasser condenser) pressure and level to increase. Control action, as discussed earlier, will be required. A setback on high bleed condenser level may result. High temperature over-ride of the bleed/degasser condenser is also possible.

Boiling in the HTS will occur when saturation conditions are reached. The increased boiling will impair fuel cooling due to film boiling and decreased coolant flow (due to pump cavitation caused by decreased suction head).

If the valve does not reclose, a reactor trip will eventually be generated on low pressurizer level (or low HT pressure where no pressurizer is installed).

Feed Pump Failure

On failure of the feed pumps, no makeup to the HTS will be available (assume for this example that no back-up pumps are available). Where pressurizers are installed, the pressurizer level will decrease while maintaining HTS pressure. This will continue until the level falls sufficiently to limit the pressurizer’s ability to react to a major upset. The unit must then be shutdown and cooled down.

In units without pressurizers, heat transport pressure will immediately begin to fall. Boiling in the HTS will occur when saturation conditions are reached. The increased boiling will impair fuel cooling due to film boiling and decreased coolant flow (due to pump cavitation caused by decreased suction head).

If the feed pump is not restored, a reactor trip will eventually be generated on low HT pressure or HTS low flow while pumps are cavitating.

Pressurizer Steam Bleed Valve Fails Open

This fault will immediately reduce the pressure in the steam space of the pressurizer and HTS pressure will fall.

Boiling in the HTS will occur when saturation conditions are reached. The increased boiling will impair fuel cooling due to film boiling and decreased coolant flow (due to pump cavitation caused by decreased suction head).

In the pressurizer, the intensive boiling will cause the level in the pressurizer to increase, causing feed valves to close and bleed valves to open (i.e. level increases due to boiling, but actual inventory is being lost through valve). A reactor trip on low heat transport system pressure is likely. Also, a setback on high pressurizer level is possible.

The flow through the steam bleed valve will cause bleed condenser (or degasser condenser) pressure and level to increase. Control action, as discussed earlier in the module will be required. A setback on high bleed condenser level may result. High temperature over-ride of the bleed/degasser condenser is also possible.

Failed HT Main Circulation Pump

The majority of operating CANDU reactors require the use of all (typically four) main HT pumps for full power operation. Loss of one pump or more will seriously impair the heat removal capability of the HTS due to low flow (ie: coolant circulation reduces while the heat input to the HTS continues). Continued operation at full power would result in film boiling in the fuel channels with a high probability of fuel failures and a large pressure increase.

On the loss of a single circulating pump at these units, a reactor stepback will occur to reduce reactor power output to approximately ~65% FP. Note that in two loop systems, trip of a symmetric pump will be required (in some situations, depending on which pump trips, a shutdown cannot be avoided).

At stations where normal operation requires 12 of 16 pumps to be operative (three out of each bank of four), the loss of any single pump in a bank, would require that a standby pump be started. Continued operation without sufficient coolant circulation would result in boiling and potential damage as stated above.

For a unit using a feed and bleed system, the resulting increase in pressure would probably overwhelm the bleed condenser capacity. The reactor may trip on high HTS pressure or temperature before the high bleed condenser level setback function is initiated.

Override of Bleed/Degasser Condenser Level Control

The description of bleed condenser and bleed cooler operation given earlier, indicates that bleed (or degasser) cooler loading is dependent upon flow (which controls level) out of the bleed (or degasser) condenser.

Thus, efforts to control a high level in the bleed condenser may produce outflows, such, that the bleed cooler can no longer cool the D_2O to 50°C or lower. Because ion exchange resins breakdown at high temperatures, additional control action is initiated to enable the bleed cooler to cool the D_2O to a temperature below that which could cause damage.

Since recirculating service water flow through the bleed cooler is always at a maximum, the only alternative to regain control is to reduce the mass flow rate of the hot D_2O through the bleed condenser (some stations have a normal fluctuating TCV on the bleed cooler). This mass flow reduction must remain in effect until the temperature at the bleed cooler outlet is again acceptable. This action will cause level control to be lost in the bleed condenser. If the condition causing the increased bleed flow is short term, things will soon return to normal. If the condition persists, rising bleed condenser level will eventually cause a reactor setback in some stations.

Similarly, temperature protection for the degasser condenser/purification design is provided in two stages. The IX resins are protected from high temperature via a similar high temperature override at the purification cooler outlet. A high temperature override also exist at the outlet of the degasser cooler to protect the feed pumps from net positive suction head problems. If the steam bleed continues (ie, HT high pressure continues, or a valve failure occurs) a reactor stepback will occur on high HT pressure (the HT relief valves also open at this point).

Summary Of The Key Concepts

- A failed open PRV will cause HTS pressure to fall. Film boiling and fuel failures are possible. Bleed condenser pressure and level will increase, with a possible setback on bleed condenser high level and high temperature over-ride. A reactor low pressure/low pressurizer level trip is possible.

- A feed pump failure will cause the HTS pressure to fall. Film boiling and fuel failures are possible. A reactor will trip on low HTS pressure or low pressurizer level/low HT pressure.

- A failed open steam bleed valve will cause the HTS pressure to fall. Film boiling and fuel failures are possible. Bleed condenser pressure and level will increase, with a possible setback on bleed condenser high level and high temperature over-ride. A reactor setback on high pressurizer level and/or a reactor trip on low HTS pressure is possible.

- The loss of HTS pump reduces coolant flow through the reactor. Continued operation at full power would result in film boiling. Reactor power reductions are required by either stepback on pump loss, setback on high bleed condenser level or high HT pressure or temperature trip.

- The bleed condenser has a high temperature over-ride to protect purification resins from damage, but this causes level control in the bleed condenser to be lost. If the HTS pressure is still high, bleed condenser level will continue to increase (bleed continues) until a setback on high bleed condenser level occurs.

- The degasser condenser has a high temperature over-ride to protect the feed pumps from damage, but this causes level control in the degasser condenser to be lost. If the HTS pressure is still high, degasser condenser level will continue to increase (steam bleed continues) until a stepback on high HTS pressure occurs (HT liquid RV's will also open at that point). Purification resins are protected from damage by a high temperature over-ride at the purification cooler outlet.

3.3 Heat Transport System Shutdown Operation

At power, a significant portion (typically 6-7%) of a CANDU reactor's full power output is due to the heating effects of fission product decay. Following a shutdown of the reactor, these fission products will continue as a thermal power source. Although radioactive decay will decrease the magnitude of this source (typically to about 1% Full Power (FP) in about 1 hour) it will still produce a significant amount of power (~20-30 MWt, depending on the station).

This unique feature of nuclear powered generating stations requires a heat removal path and heat sink at all times when the reactor contains used fuel. This means that at least a portion of the HTS must be available to remove the decay heat from the fuel.

Since this decay heat is always present, the cooling systems required to remove decay heat are supplied by Class III power (or at least backed up with Class III power) to ensure a reliable power supply (i.e., a reliable heat sink).

Without this continuous cooling, it is easily possible to fail fuel even with the reactor shutdown. For example, insufficient cooling of a tripped reactor caused the massive fuel failures that occurred at Three Mile Island. Fuel failure will inevitably release fission products into the HTS, reducing the multiple barriers to the release of radioactive contaminants.

This section will deal with the heat removal paths while shutting down the reactor, and while the reactor is shutdown. The emergency use of shutdown cooling and maintenance cooling systems will also be covered.

3.3.1 Types Of Shutdown Cooling Systems

The systems in use vary between stations and are known either as directly cooled or indirectly cooled. All make use of at least a portion of the heat transport system with one or more heat exchange points before arriving at the final heat sink (lake, river, or sea).

Directly cooled refers to systems where the HT D_2O is cooled directly by service water. This type of cooling is used for shutdown cooling in stations where the preheaters are not external to the boiler.

For the indirectly cooled case of shutdown cooling, the initial heat exchange is from HTS coolant to boiler feedwater. This heat exchange occurs in preheaters external to the boilers (installed only in some stations), while the boilers themselves are not involved. The second heat exchange is from the feedwater to service water, which carries heat away to the final heat sink (the lake river or sea). This is an indirect system. This method of cooling requires the boiler feedwater system to be in service, and HT pumps operating.

A separate directly cooled system, known, as the Maintenance Cooling System (MCS) is available on units with indirect shutdown cooling systems. This system allows the feedwater system and HT pumps to be shutdown when maintenance on the feedwater or HT system is required. This system has a heat removal capacity of approximately 1% FP.

Partial draining of the HTS (down to header levels) for maintenance purposes may also be performed on some units with direct shutdown cooling systems (or maintenance cooling systems).

The representative heat removal chains for the above are shown in Figure 3.12.

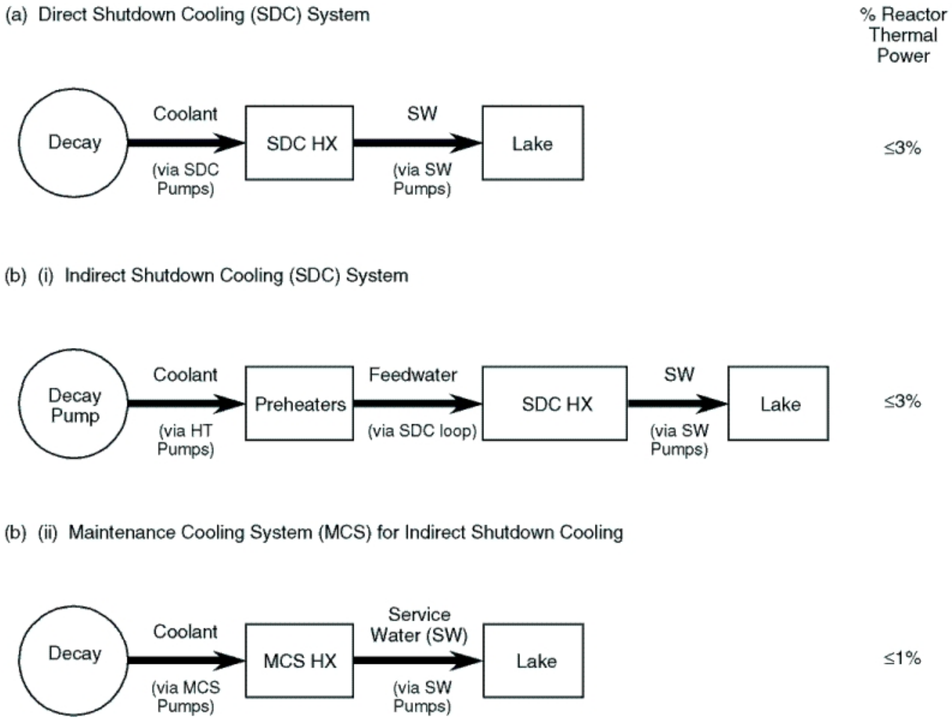


Figure 3.12
Heat Removal Chains

Steam Reject Cooling

For both types of systems (direct and indirect), the initial HTS cooldown from full power operation (ie, from up to 300°C to between 150°C-165°C) is normally achieved by Boiler Pressure Control (BPC) system using steam discharge to the atmosphere or condenser. The shutdown cooling system will then continue the cooldown.

It should be noted that steam reject cooling could (theoretically) continue to near 100°C as boiler pressure is lowered, but is not desirable (since the steam volume produced would be enormous). As the temperature decreases, the rate of HTS cooling would also decrease because the differential temperature between the HTS and the boilers decreases. The large volumetric flow of steam produced at lower boiler pressures may choke the steam valves and limit cooldown rate. This would result in spending too much time in the higher risk temperature range for pressure tube delayed hydride cracking.

Directly Cooled Shutdown Cooling System

System Description

A typical system is shown in Figure 3.13 and consists of a pump and heat exchanger combination in parallel with the normal full power heat removal path. The number of shutdown coolers varies from location to location, but there is a minimum of two cooler loops at any location. Note that the normal flow direction through the reactor is maintained by the shutdown cooling pumps. No redundancy of shutdown cooling pumps (in a loop) is provided, as the total shutdown cooling flow is typically 10-15% of the main system flow. Adequate shutdown cooling flow can be maintained with a single shutdown cooling loop unavailable.

On a controlled cooldown, the heat removal capacity requirement is for approximately 1-3% of reactor full power.

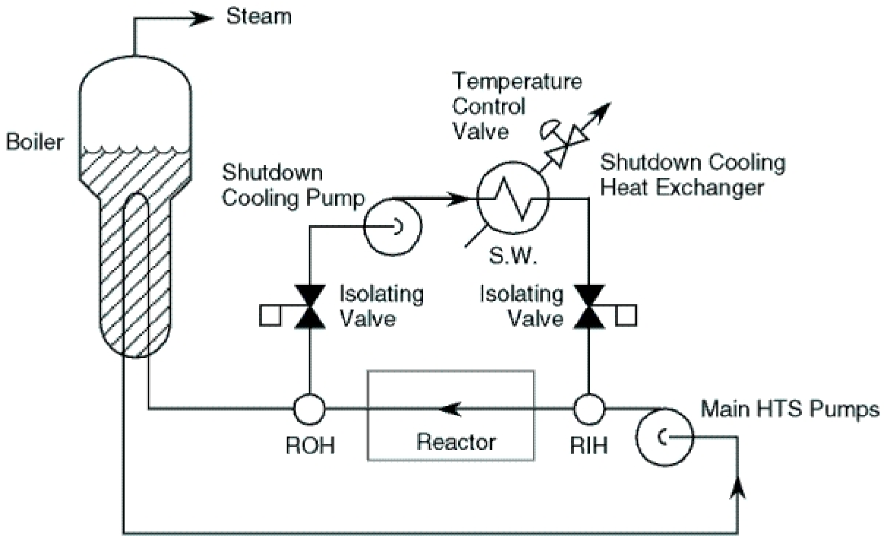


Figure 3.13
Simplified Directly Cooled Shutdown Cooling System

Typical Operation

With the reactor at power, the shutdown cooling isolation valves will be closed. The shutdown cooling loops will be filled with pressurized D_2O via small lines from the reactor outlet headers. The shutdown cooling loops are also warmed to a temperature close to the HTS temperature by the use of warmup lines from the HTS (not shown in the diagram), before being slowly valved into service. This avoids thermal shocks to the system.

During a cooldown of the HT system following a reactor shutdown, the shutdown cooling system will be used to cool down the HTS from ~165°C to 60°C (remember that cooldown from operating temperature to ~165°C is by steam reject). Temperature control of the shutdown cooling system is achieved by automatic control of service water flow through the heat exchangers (In some plants, 2 or 4 main HT circulating pumps will continue to operate until a low system temperature is achieved. Shutdown cooling can then continue with the HT pumps shut off).

Note that it is important to establish a cooling water flow prior to placing the system in service. Failure to do this could result in boiling on the cooling water side of the heat exchanger. When the cooling water flow is established, the vapour pockets would collapse (due to condensation), which could result in water hammer.

Indirectly Cooled Shutdown Cooling System

System Description

External preheaters are used at some stations to provide cooler D_2O to the inner zone of the reactor, where the channel temperature differentials (ΔTs) are higher than those for the outer zone. Other stations use increased coolant flow rate in the channels with higher channel powers (inner zone).

In stations with external preheaters, coolant for the inner zone channels, which has already passed through the boiler tubes, is routed through the preheater tubes. Here it releases additional heat to preheat the boiler feedwater on the shell side. Thus, pre-cooling of HTS D_2O (for the inner zone of the core) and preheating of boiler feedwater are accomplished in the preheater.

The basic system for indirect cooling is shown in Figure 3.14 on the next page. It is somewhat more complicated than the direct method because two heat exchange points are required (refer back to Figure

3.12). The initial heat removal path is from the HT D_2O to the boiler feedwater in the preheaters, with a secondary heat exchange from the boiler feedwater to service water in the shutdown coolers (heat exchangers).

Note that the system must remove the heat input to the HTS by the main HTS pumps, as well as the decay heat. This increases the heat removal capacity to ~3% FP

Typically the system consists of 2 x 50% heat exchangers and 2 x 100% pumps. Power supplies are typically Class III to ensure a reliable power source for fuel cooling.

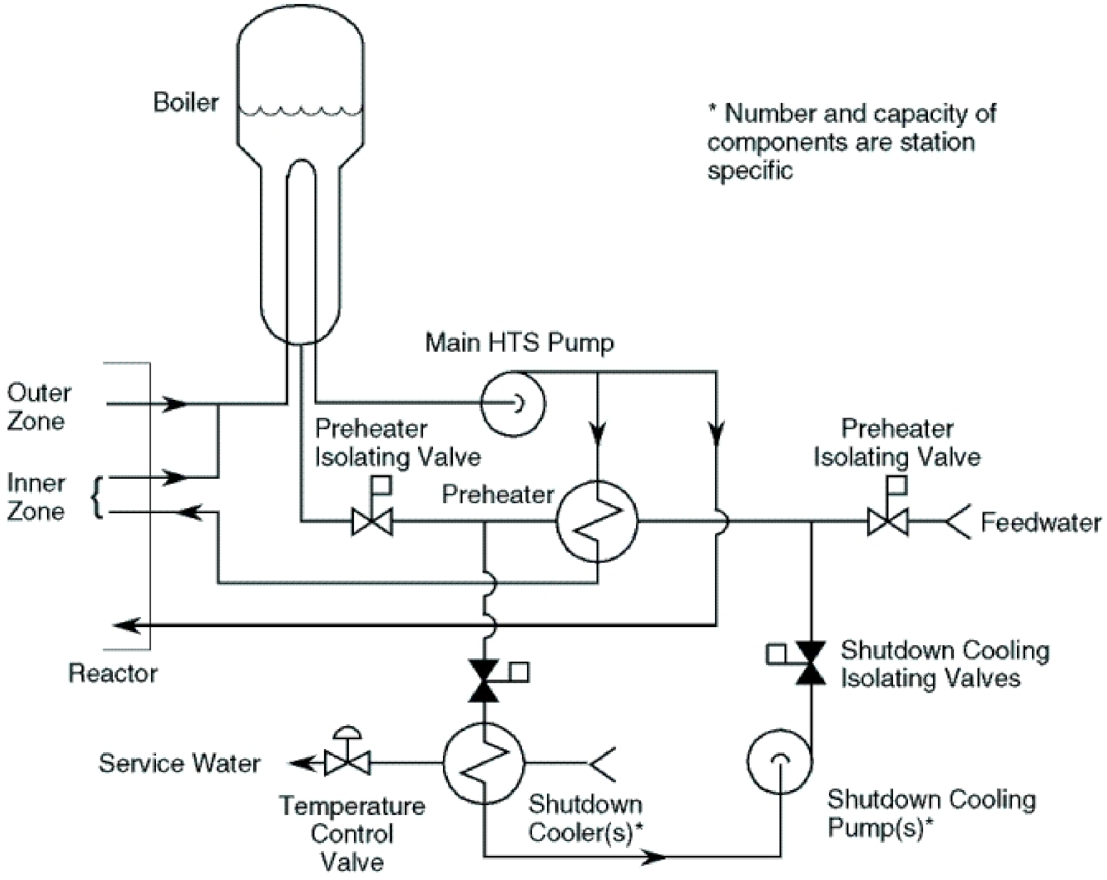


Figure 3.14
Typical Indirectly Cooled Shutdown Cooling

Typical Operation

With the reactor at power, the shutdown cooling loop is kept in a cold depressurized state and isolated from the preheaters. The system must be filled and vented prior to use, to prevent water hammer due to slugs of water being forced through the system.

As with the direct system, this shutdown cooling system normally cools the HTS from ~165°C to 60°C.

The system is brought into operation by opening the shutdown cooling isolation valves. HTS temperature control is provided by a temperature control valve on the service water line to the heat exchanger.

It is important to keep the feedwater portion of the system pressurized. Failure to do this will result in boiling in the system. The vapour pockets formed will collapse when the vapour is condensed in the heat exchanger, or if the system is pressurized quickly, resulting in water hammer.

Note that the HT pumps must remain in operation to circulate D_2O through the preheater. Since the HTS is pressurized when the main pumps are in operation, the final state of the HTS under shutdown cooling is cold and pressurized.

Loss of the main HT pumps during a cooldown will result in inadequate heat removal via the preheaters due to loss of coolant circulation. Thermosyphoning will be required to remove the heat that was being removed in the preheater until maintenance cooling is put into service.

Maintenance Cooling System

As noted earlier, indirect shutdown cooling systems are only suitable to bring the HTS to a cold pressurized state, (Reduce HT temperature from ~60°C to ~30°C).

The maintenance cooling system is used to take the HTS down to a cold depressurized state.

If maintenance requires the HTS to be depressurized and/or partially drained to header levels, or maintenance is required on the feedwater system, some alternative form of cooling must be provided. The maintenance cooling system will meet this requirement. It’s simplified layout is shown in Figure 3.15. Note that only a single loop is used. This loop is physically located at a low level to allow partial draining of the HT system to header level. The system is also capable of cooling the HTS after BPC cooldown under emergency situations (ie, if shutdown cooling is unavailable).

During normal system operation, the maintenance cooling system is isolated from the HTS.

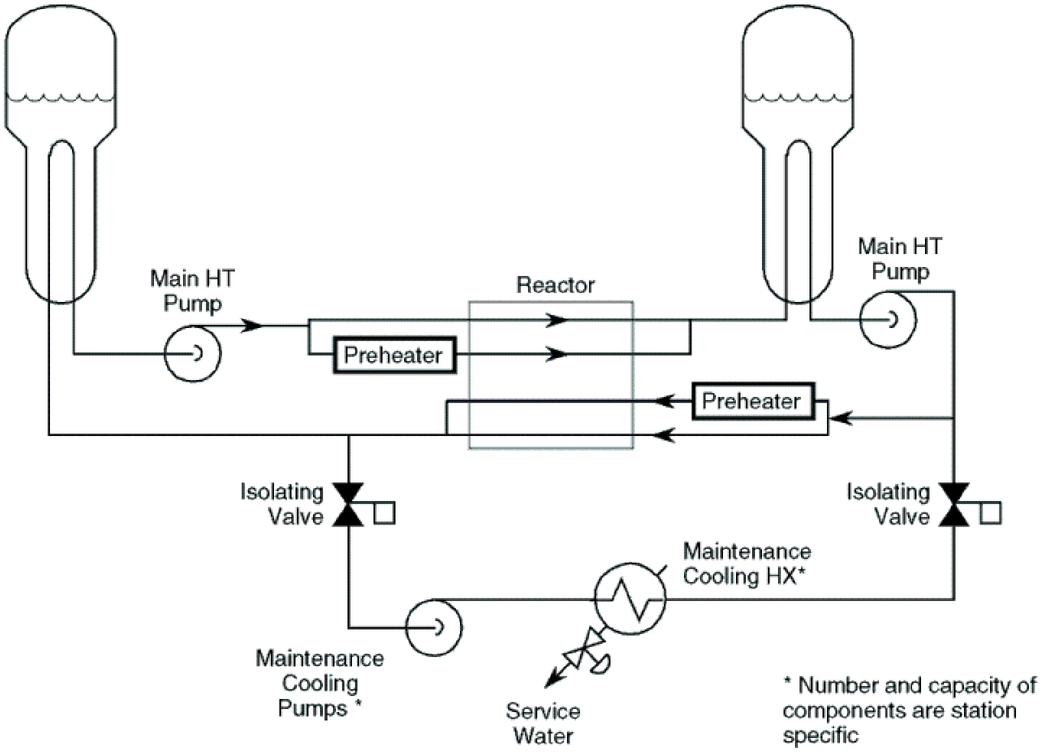


Figure 3.15
Typical Maintenance Cooling System

3.3.2 Summary Of The Key Concepts

- The HTS must be available at all times to remove fission product decay heat from the fuel. Power supplies to systems that cool the reactor when shutdown are normally from Class III power, to ensure a reliable power supply.

- Direct cooling systems cool the HTS D_2O to provide cooling while shutdown. Indirect cooling systems cool the feedwater, which indirectly cools the HTS D_2O in the preheater.

- The shutdown cooling system must remove decay heat to reduce HT temperature from ~165°C to ~60°C. The final state on shutdown cooling is cold and pressurized. Heat removal requirements are ~1-3% of reactor full power for a controlled cooldown. For direct cooling systems, the unit can be depressurized to allow maintenance on the system.

- The maintenance cooling system must remove decay heat to reduce HT temperature from ~60°C to ~30°C. The final state on maintenance cooling is cold and depressurized (and possibly drained to header levels). Heat removal requirement is ~1% of reactor full power.

- The maintenance cooling system is capable of cooling the HT system after steam reject cooldown.

3.3.3 Thermosyphoning

At full power operation, Class IV power is required for the main HTS circulating pumps and boiler feed pumps to ensure heat transfer and removal. If Class IV is lost, full power heat transfer capability is also lost and the reactor will trip either on low HT flow or high HT pressure (due to coolant swell, as average HT D_2O temperature increases).

After a loss of Class IV and the resultant reactor trip, some HTS circulation will be maintained by the inertia stored in the HTS pump motors/flywheels for a 2 to 3 minute period. This circulation, although reduced, continues to transport heat from the fuel to the boilers. During this period, the total heat input (fission, decay, and residual pump heat) is reduced to about 3% of full power values. The final heat sink is usually steam discharge to atmosphere via the SRVs or ASDVs (depending on the station).

Following motor/flywheel rundown, heat can still be transported to the boilers by a process of natural convection known as thermosyphoning.

The layout of a CANDU unit ensures that the boilers are at a higher elevation than the reactor. The cooling action in the boiler will increase the density of the D_2O coolant causing it to fall back to the reactor. This will force the hot, lower density, D_2O to rise from the reactors to the boilers. A continuous flow pattern is thus established.

Cooling can be maintained indefinitely by this process providing the following criteria are maintained:

1. Reactor power is limited to ~3% FP or less (ie, decay heat levels).

2. Boiler Pressure Control is functional to maintain the ΔT between HT D_2O and boiler water. This will ensure that the HT D_2O density differences are maintained to drive the thermosyphoning flows.

3. A boiler heat sink is available, ie, SRVs or ASDVs plus a guaranteed supply of boiler feedwater (requires Class III power for auxiliary boiler feed pump & BLC to maintain boiler level above top of tube bundle).

4. HTS pressure and inventory control is operational. If HTS pressure cannot be maintained, boiling may occur in the reactor outlet headers. If excessive boiling were allowed, flow may not be maintainable under two-phase (liquid and vapour) conditions.

The heat transfer paths following loss of Class IV power and under thermosyphoning conditions are shown in Figure 3.16.

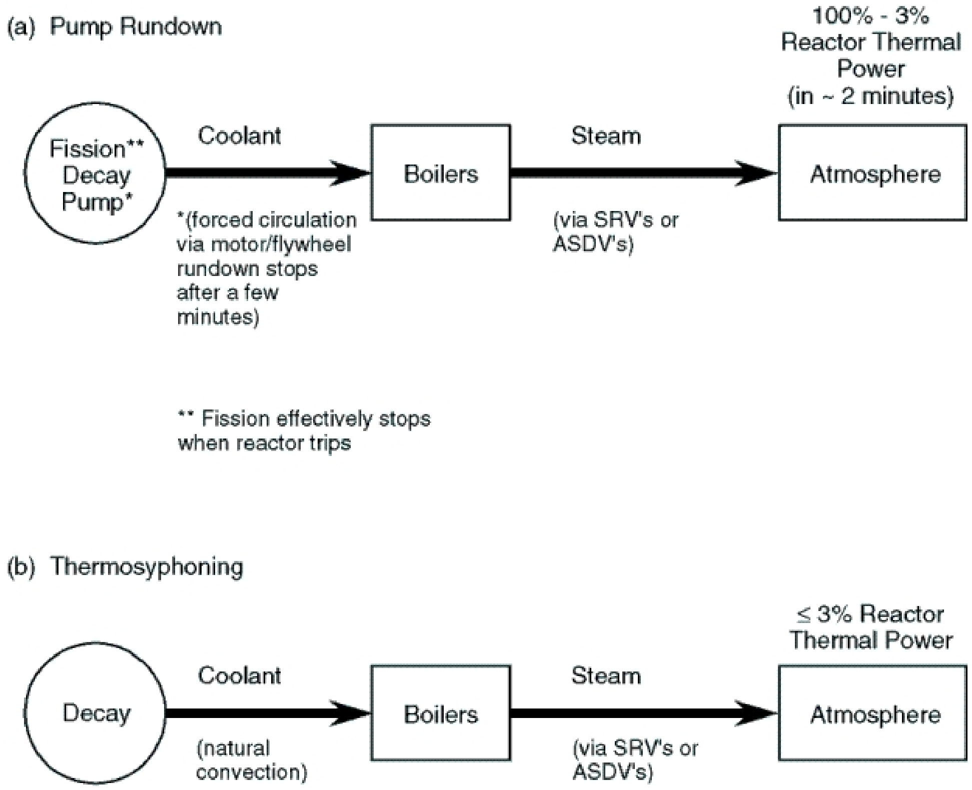


Figure 3.16 - Heat Transfer Following Loss of Class IV Power

3.3.4 Crash Cooldown

Crash Cooldown is a procedure which quickly reduces heat transport system temperature following a system upset.

Boiler pressure (hence, boiler temperature) is rapidly reduced by discharging steam to atmosphere using either steam reject valves or instrumented safety valves. This rapid reduction in boiler temperature will cause a corresponding increase in heat transfer rate from the HTS due to the larger ΔT, thus rapidly lowering its temperature.

This procedure will subject system components to extreme thermal stresses. A full crash cool (ie: all available steam rejected to atmosphere) would normally only be effected if a LOCA occurs. For other unit upsets, which may require rapid cooling of the HTS, a sufficiently fast cooldown will usually be achievable with less than the full complement of steam discharge valves in use.

The heat transfer path for crash cooldown is shown in Figure 3.17

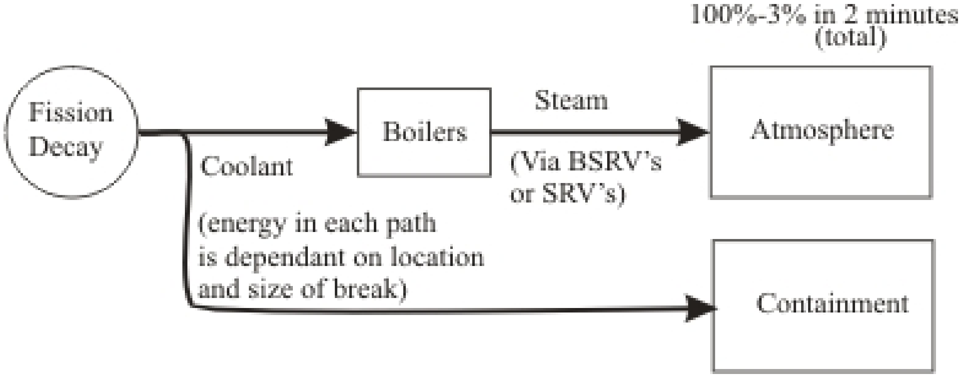


Figure 3.17
Crash Cooldown Heat Transfer Path

3.3.5 Emergency Cooling Using Shutdown Cooling

If normal cooldown using BPC is not available, or undesirable due to a large number of boiler tube leaks emergency cooldown of the HTS (immediately following a trip) can be achieved using only the shutdown coolers by valving in the system without a prior warm-up.

The system is designed to withstand the thermal shock that will accompany this procedure, but for a limited number of times only, Extensive repairs, inspections or equipment replacement will be required if this limit is reached.

Following an emergency cooldown, a thorough inspection of the shutdown coolers must be carried out and tube sheet integrity assured.

The normal maximum capacity requirement for the shutdown coolers during an emergency cooldown is ~6-7% of full reactor thermal power.

At stations using a maintenance cooling system, this system can be placed in-service at ~160°C in an emergency situation. This could occur if the shutdown cooling system was unavailable for service during cooldown. This cooldown would be carried out at a suitable HT pressure to meet net positive suction head requirements of the maintenance cooling pump and extensive system inspections would follow.

3.3.6 Summary Of The Key Concepts

Thermosyphoning is achieved by natural convection between the reactor and the boilers. In the boilers the D_2O is cooled by the boiler water and then falls back to the reactor due the increased density of the D_2O. Hot D_2O is forced up into the boilers where additional heat can be removed. This method of heat removal is capable of removing ~3% reactor full power. Four conditions required to maintain thermosyphoning are:

- Reactor power $\leq$ 3% FP (ie, decay heat),
- BPC is functional to maintain ΔT between HT D_2O and boiler water in the boilers.
- SRVs or ASDVs are available with a feedwater supply for heat rejection,
- HTS pressure and inventory control system available to prevent HTS boiling.

Emergency cooldowns are possible by placing the shutdown cooling system in service at elevated temperatures. Placing this system in service for emergency cooldown subjects the system to high thermal stresses. Inspections of components would be required following an emergency cooldown. The number of times that this system is capable of emergency cooldown is limited. The system capacity required is ~7% reactor full power.

Crash cooldown is a rapid reduction in HTS temperature caused by discharging large amounts of boiler steam to atmosphere.

3.4 HTS Heavy Water

A primary distinguishing feature of the CANDU reactor is the use of heavy water (D_2O) both as a moderator and coolant. This section covers the HTS coolant and its requirements with respect to D_2O quality and standards. Radiological hazards of the HTS coolant will also be discussed.

3.4.1 Isotopic Limits

Remember that D_2O quality is usually expressed in terms of the percentage of D_2O and H_2O, i.e. isotopic content.

For day-to-day operation of a CANDU unit, a lower limit is placed on D_2O coolant isotopic. This lower limit is set for two basic reasons: economy and safety.

Economy

Although the coolant plays a very minor role in terms of thermalizing fast neutrons, H_2O in the coolant will directly affect the amount of neutrons absorbed and therefore, removed from the neutron cycle. For example, it is probable that with an HTS isotopic of 90% (ie, 10% H_2O), the reactor Regulating System (RRS) could still maintain criticality. However, this would be done at the expense of a higher fuel usage. This fuel penalty must be traded off against the higher production and upgrading costs.

Safety

From a safety point of view, isotopic requirements are related to the potential for voiding in the HTS and the accompanying reactivity effects, particularly as a result of a LOCA.

The presence of H_2O in the coolant increases neutron absorption. Maintaining criticality requires the addition of reactivity worth (ie, lowered zone levels, etc.).

At the onset of a LOCA, pressure in the fuel channel is reduced, resulting in boiling and formation of voids. The neutrons that were previously being absorbed are now available for fission. Positive reactivity will increase rapidly. Thus, RRS or the special safety systems must maintain the coolant isotopic at a level such that the excess neutrons available through voiding are controlled. The normal minimum isotopic value is set by OP&P's at between ~97.5% and ~98.5%.

For example, it has been calculated that a typical CANDU reactor (600MW) operating with equilibrium fuel and moderator and HTS isotopic of ~99.7% could experience an increase in reactivity up to 10mk depending upon the degree of voiding.

In most stations, an upper limit for heat transport system isotopic also exists for safety reasons. An upper limit on HTS isotopic limits the rate and magnitude of positive reactivity inserted during an in-core LOCA. This upper limit is usually expressed as a minimum difference between HT and moderator isotopic, with the moderator isotopic being the higher of the two.

Say, for example, that a unit is operating and a LOCA with high isotopic D_2O occurs into the moderator. Any neutron poisons (eg: boron) present in the moderator will be displaced or diluted. This would result in an increase in reactivity, since the neutrons that were previously being absorbed by the poisons are now available for fission. The limits specified in your station will depend on maximum boron (or equivalent poison) loads allowed (eg: excess reactivity, for fueling ahead), reactor design, moderator isotopic and shutdown system depth (to protect against in-core LOCAs while shutdown and not in the GSS).

3.4.2 Downgrading of HTS D_2O

The following mechanisms downgrade HTS D_2O during normal operations. All are attributable to H_2O ingress or formation.

1. Accidental additions of downgraded makeup or collection returns
2. Use of improperly deuterized IX resins in the HTS purification circuit.
3. Hydrogen addition to the HTS (to be discussed later)
4. H_2O from air in-leakage to HT D_2O collection system and storage tank (particularly if the systems are opened for maintenance).

The first two sources can potentially be large sources of downgrading. The last two sources will produce small but continuous sources of downgrading.

Table 3.1 gives some of the expected short and long-term operating effects resulting from changes in D_2O isotopic.

Table 3.1
Effects of Isotopic Changes on Operation

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
1. Isotopic slowly increasing due to virgin or upgrader D_2O additions for makeup (typical max ~ 0.05%/mthly	No observable effect, isotopic change too small	Fuelling rate (bundles/week) reduced slightly. Higher average fuel burnup.
2. Sudden downgrading by $\leq$ 3% to the lowest isotopic allowed by Operating Policies and Principles.	Operation continues with a drop in average liquid zone level (adjuster(s) possibly out).	Increased fueling rate needed to return (and maintain) zone levels/adjusters to normal operating positions. Lower average fuel burnup.
3. Sudden downgrading to below the limit in (2).	As above, unless drop in Δk is large enough to make reactor subcritical.	Reactor should be shutdown until minimum HT isotopic is available.

3.4.3 Radiological Hazards

The management and control of HTS coolant inventory must also take in to account the radiological hazards that are present under different operating conditions.

During normal power operation, the coolant will contain:

1. Coolant activation products: Tritium, Nitrogen-16 (N^{16}), Oxygen-19 (O^{19}).
2. Fission products (principal source is failed fuel):
   a. Halogen fission products, mainly Iodine-131 (I^{131})
   b. Other gaseous fission products (mainly noble gases)

3. Activated corrosion products: mostly metallic isotopes created by a combination of activation and corrosion of HTS components.

The activated corrosion products will be distributed around the system and will tend to plate out usually around pipe elbows and valves. The γ will be capable of penetrating the pipework, causing an external dose hazard while operating and when shutdown. Some of the corrosion products will also emit β particles. This will pose an external β hazard if the HT D_2O leaks from the system, allowing these materials to leave the system. These hazards are greatly increased when carrying out maintenance on system components (eg, close proximity to components or the system is opened).

Most of the gaseous fission products (noble gasses) are short lived and will decay to very low levels in 1 day or less, hence are a major hazard normally only while operating. These contribute to the external dose hazard as mentioned above. In addition to the above, some noble gasses, in high concentrations, can result in external β hazards (due to a β-γ decay).

Iodine-131 has a half-life of ~ 8 days. Other radioiodine isotopes will decay in 1 day or less. The source of the radioiodines is failed fuel. The ion exchange columns in the HT purification system will remove the iodine from the system, but some iodine may still be present. Any leakage of coolant from the HT system releases I^{131}, which can result in an uptake to plant personnel.

Under normal conditions (with the coolant contained within the system) the significance of the above radiological hazards is reduced somewhat due to the shielding provided by the system itself. But, N^{16} and O^{19} are produced in the core and are high-energy gamma emitters, which presents an external γ radiation dose hazard. There is also a neutron hazard as a result of the decay of N^{16} (which emits high-energy γ, which reacts with deuterium, resulting in a photoneutron emission). These hazards are somewhat controlled since the majority of the HTS is inaccessible when at-power (i.e.: within containment or access controlled). Following a shutdown, the formation of activation products will cease and N^{16} and O^{19} will quickly decay (in minutes) to negligible levels.

Any leakage of coolant from the HT system presents a major radiological hazard. The external γ hazard still exists (due to D_2O in the HTS and due to halogen fission products leaking from the HTS,

N^{16} and O^{19}), but now is accompanied by a tritium hazard (internal β) and, possibly I^{131}. Note that this will be in addition to the conventional hazards posed by hot, pressurized liquids.

3.4.4 Summary Of The Key Concepts

- The HTS has minimum isotopic limits for fuel economy and reactor safety (voiding effects).
- The HTS has maximum isotopic limits for reactor safety (protection against in-core LOCAs).
- The four major sources of HTS downgrading are accidental additions of downgraded D_2O, improperly deuterized IX resins, formation of H_2O from H_2 addition and air ingress.
- The addition of downgraded D_2O to the HTS is a major concern because of the economic consequence of downgrading.
- Radiological hazards of HTS D_2O exist while at power and when shutdown. The sources of this hazard are coolant activation products, halogen fission products, gaseous fission products and activated corrosion products.
- While shutdown, the four major radiological hazards are from external γ, external β, tritium and I^{131}.
- While at power, the two major additional radiological hazards are from high energy γ from N^{16} and O^{19} and photoneutrons as a result of the decay of N^{16}.

3.4.5 Heat Transport System D_2O Collection Systems

D_2O is very expensive. Chronic, unrecovered losses can impose an economic penalty on unit operation. In addition, it also poses a radiation hazard to personnel.

Since the majority of the HTS operates at high pressure, the likelihood of leakage is increased. In fact, some equipment will leak small amounts of D_2O during the course of normal operation (eg: pump seals).

HTS D_2O Collection System

This system is provided to collect the normal, expected leakage from the HTS. It consists of a closed piping system connected to the various equipment collection points.

Typical collection points are:

- Main circulation pumps seals.
- Bleed cooler drain/vent lines.
- HTS vents.
- HTS valve glands.

The leakage will drain by gravity to a collection tank. The rate at which this tank fills will give an early indication of any high leakage rates.

A representative HT collection system is shown in Figure 3.18

Since much of the D_2O collection is hot, a cooling system is sometimes provided in the collection tank. Cooling water is passed through tubing immersed in the collection tank. This is a potential source of D_2O downgrading if tube leaks occur.

Any hot D_2O vapour is condensed in a vent condenser and the condensate returned to the collection tank. The vent condenser is also a possible source of D_2O downgrading.

The collection tank is provided with a high level alarm. When this alarm comes in, the tank contents are recirculated by a pump to ensure thorough mixing of the contents (2 x 100% pumps are usually provided), and are then sampled.

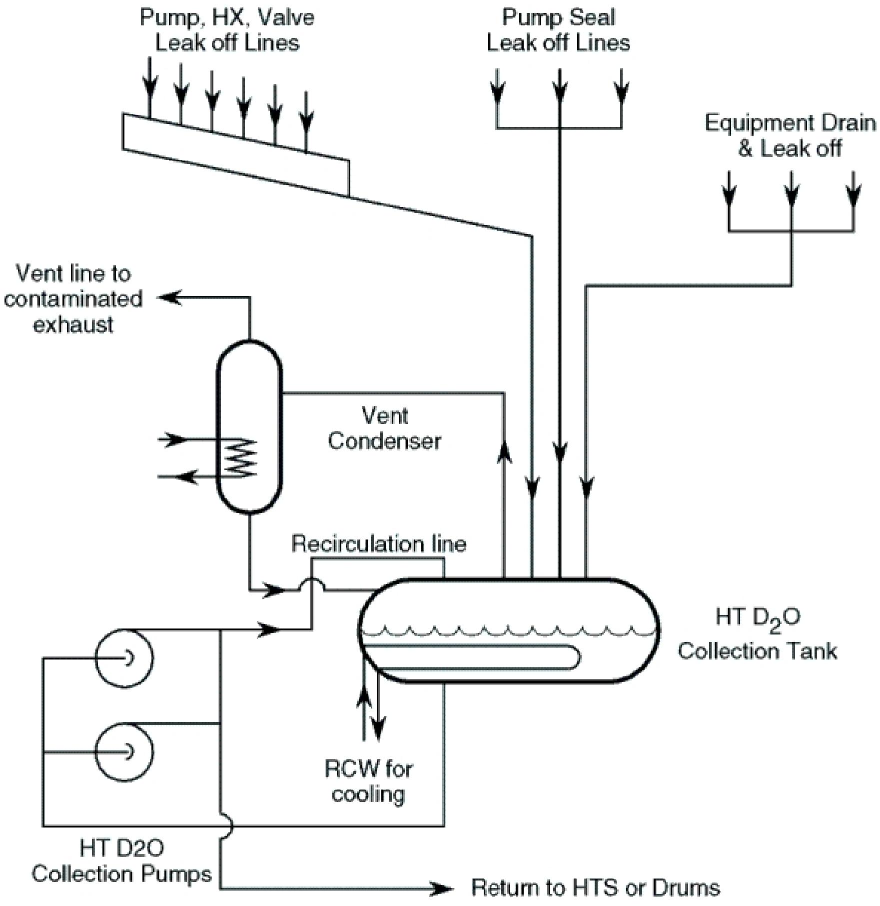


Figure 3.18
D_2O Collection System

Leakage to this tank is not normally downgraded. However, before returning it to the heat transport system, its isotopic should be checked to ensure it meets the station minimum requirement for the same economic and safety reasons mentioned at the beginning of the module. This D_2O must also be free of contaminants. If this D_2O is contaminated, activation of the contaminants or corrosion of the HTS may occur.

Miscellaneous D_2O Collection System

There are sources of D_2O from leakage points (throughout the reactor system) which likely do not meet specifications for return to the system, These collection points are routed to the miscellaneous D_2O collection system. Possible sources are the HTS collection tank if contents are outside specification, the feed pump bearings and the contaminated exhaust.

For this system, the collected D_2O is fed to the upgrader or to drums.

Vapour Recovery System

D_2O leakage into the reactor vault atmosphere will form D_2O vapour, particularly when the air temperature is above normal ambient temperature. Note that reactor area vapour will not be exclusively D_2O, but will contain H_2O and other components.

Extraction blowers route vapour to a vapour recovery system. This system usually consists of desiccants that absorb the vapours. Heaters regenerate saturated desiccant and release concentrated vapour to a condenser. The recovered liquid must then be returned to upgrading since it will be downgraded by the H_2O etc., in the liquid. This system provides four advantages:

1. It recovers expensive D_2O.
2. It allows the detection of small chronic leaks.
3. It reduces the atmospheric radiation levels due to tritium.
4. The extraction action (through the purge driers) reduces containment pressure to slightly subatmospheric, thus inhibiting out-leakage to the station and the environment.

A typical NGS may have more than one vapour recovery system serving areas such as the reactor vault, fueling machine duct, and fueling areas.

Liquid D_2O Recovery System

The Liquid D_2O Recovery System, installed in most station, allows the reactor to be shut down in a controlled manner in the event of a small piping rupture. The system will return sufficient D_2O to the HTS to maintain cooling in the fuel channels until the HTS can be cooled and depressurized. Small rupture indicates that HTS pressure can be maintained, ie: coolant input capability to the HTS is greater than coolant losses.

For small HTS ruptures, D_2O Recovery precludes ECIS initiation with the following adverse effects:

- major downgrading of coolant as a result of light water injection

- forced shutdown of the other units at multi-unit stations
- thermal stresses created by crash cooling and cool ECIS water

The basic system is shown in Figure 3.19.

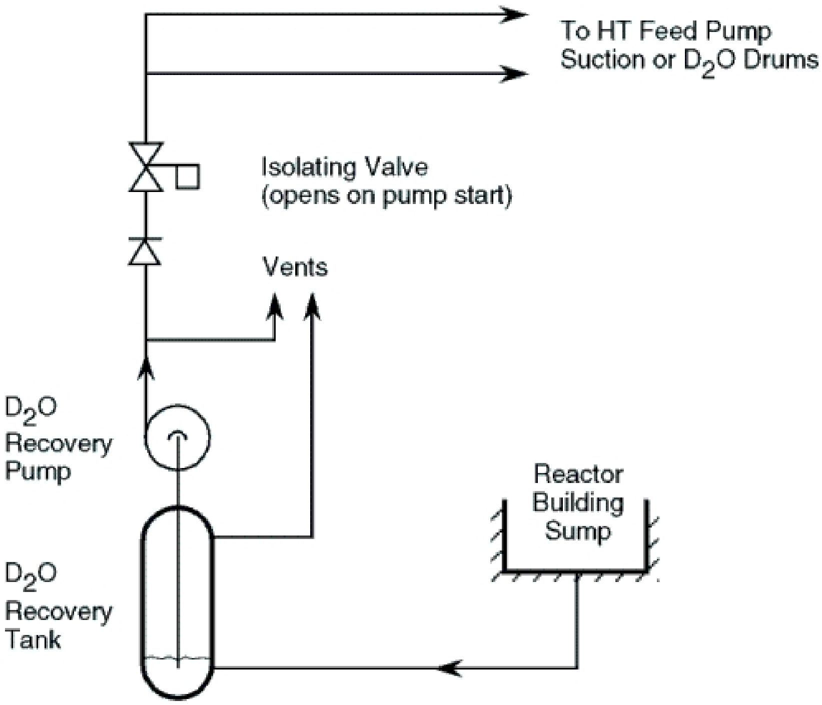


Figure 3.19 - D_2O Recovery System

D_2O from the leak gravitates to a sump and then to a recovery tank, located at a low level in the reactor building. D_2O from this storage tank can be pumped either to HTS feed pump suction or, if the leak rate is small enough, to drums for subsequent chemical clean up and upgrading. The unit's D_2O storage tank can supply any needed make-up via inter-unit tie (in multi-unit stations).

If leakrate is within system design capacity, it is unlikely that the steam produced by a small HTS rupture will initiate containment operation. The pressure rise in the reactor building will not likely exceed the containment PRV operating setpoint (for negative pressure containment systems).

3.4.6 Summary Of The Key Concepts

- HT D_2O collection system collects leakage from various points in the HTS system where the collected water will likely meet specifications for return to the system. This D_2O must be checked for isotopic for the same safety and economic reasons mentioned earlier in the module. Chemical purity must also be checked to ensure that corrosion in the HTS and activation of any contaminants is minimized.

- Miscellaneous D_2O collection collects leakage from other places in the HTS system where the collected water will not likely meet specifications for return to the system. This water is drummed or sent directly to upgrading.

- The vapour recovery system recovers D_2O vapours from various locations in the station, allows detection of small chronic leaks, reduces atmospheric levels of tritium and keeps containment pressure sub-atmospheric.

- The liquid recovery system returns sufficient D_2O to the HTS to maintain adequate system inventory to ensure fuel cooling in the event of a small pipe break. This water is recovered from sumps inside containment and will likely be dirty or downgraded.

3.4.7 HTS D_2O Leaks

The various D_2O collection and recovery systems described can be used as a good indicator of HTS leakage and leak rates, as can D_2O storage tank level.

Chronically high leak rates have several potentially severe consequences. They are:

1. Release of radioactivity (mainly tritium) to the plant and possibly the environment.

2. Potential loss of HT pressure control with subsequent fuel cooling problems.

3. Economic burden: increased replenishment and upgrading costs.

Other Leakage Indications

Other potential leak points may require additional indications other than those related to D_2O recovery rates. Two such examples are pressure and boiler tube leaks

Pressure Tubes

An early indication of a pressure tube leak can be provided by continuously monitoring the dew point of the annulus gas. This reading will only indicate that a pressure tube is leaking - identification of the particular pressure tube will require the use of other identification methods. Thus, a leaking pressure tube may be a pre-warning of a LOCA, with its adverse effects.

Boiler Tube Leakage

A leak in a boiler tube(s) will cause high pressure D_2O to enter the secondary system. The consequences will vary depending upon the magnitude of the leak. For example, several leaking (broken) boiler tubes can cause HT pressure to drop and level in the affected boiler may increase due to the inventory transfer from the HTS to the boiler (this is a LOCA). On the other hand, a small boiler tube leak will not cause such drastic control problems.

A common consequence for all sizes of boiler tube leaks is the release of radioactivity, principally tritium, into the steam system. This causes the following consequences:

a. Containment has been breached. Radioactivity can be released into the environment by unmonitored routes, eg, Boiler Blowdown and Condenser Air extraction, Atmospheric Steam Discharge Valves (ASDV) or Steam Reject Valves (SRV).

b. The D_2O is unrecoverable, constituting an economic penalty.

3.4.8 Summary Of The Key Concepts

- An abnormally high leakage collection rate could result in:
    - Release of radioactivity,
    - Potential loss of HT pressure control and fuel cooling,
    - Economic penalty.

- Pressure tube leaks must be corrected since they could result in a LOCA from a failure of the pressure tube.
- Boiler tube leaks result in:
    - unmonitored releases of radioactivity,
    - unrecoverable D_2O.

3.5 HEAT TRANSPORT SYSTEM AUXILIARIES

This section deals with a number of auxiliary systems essential for ensuring the reliable and prolonged operation of the Heat Transport System (HTS).

The systems described are:

1. HTS Purification
2. HTS Hydrogen Addition
3. HTS Main Pump Gland Seal Supply

3.5.1 Heat Transport Purification System

Your previous R&A courses have already described the equipment (filters, strainers, and ion exchange columns) required to purify HTS coolant.

Basically, the purification process has two main purposes:

a) To maintain HTS chemical parameters at specified levels.

b) To remove impurities (crud) from the HTS

The method of providing the flow to the purification system is site specific. In most stations, purification occurs at a reduced pressure (300-1000 kPa). In other stations, purification occurs at full HTS pressure (9-10 MPa). However, some common parameters exist. A typical purification system arrangement is shown in Fig. 3.19.

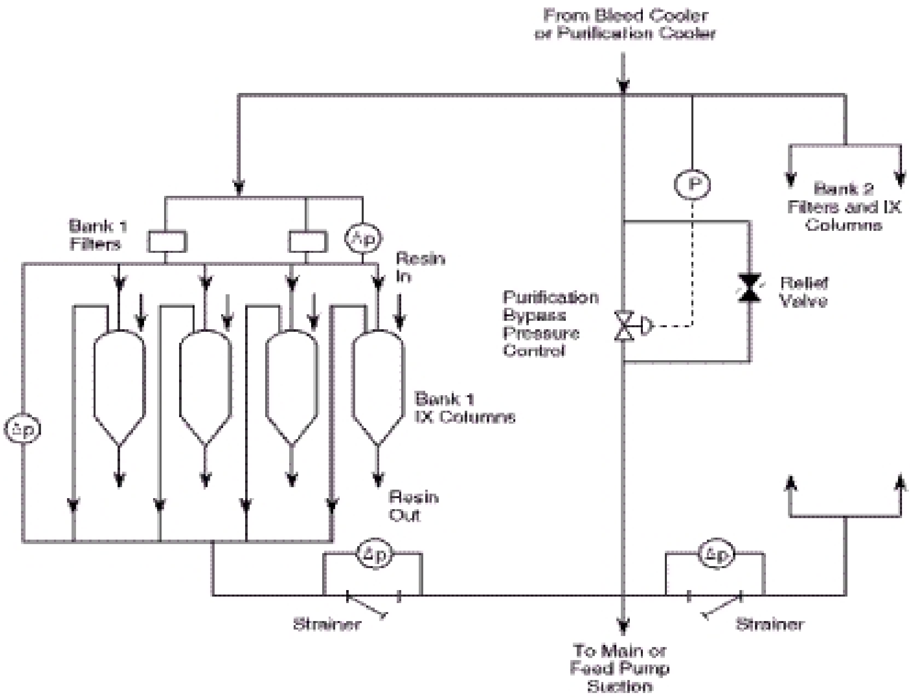


Figure 3.19
Typical HT Purification System

To ensure proper operation of this system, the following parameters must be maintained within their limits:

a) Inlet temperature

b) Flow

c) ΔP across the system

d) Inlet pressure

Each of these parameters is described in detail below.

Inlet Temperature

The temperature of the D_2O coolant feed to the IX columns is limited to below 65°C to protect the IX resins from damage. A high temperature in D_2O supply to the IX columns can have the following possible consequences:

a) Reduction in ion exchange efficiency (particularly anion).

b) Risk of IX bead melting and subsequent migration into the HTS.

c) Release of any residual chemicals (eg. chlorides, fluorides) that may exist in the resin. This increases the risk of stress corrosion problems with zircaloy and stainless steel components.

To prevent these consequences, the HTS purification flow must be cooled from reactor operating temperature (~250°C) when the unit is at power. At most stations, a combination of a bleed condenser and bleed cooler provide the necessary temperature (and pressure) reduction. At the other stations, where purification occurs at full HTS pressure, two interchangers and a cooler provide the cooling. In both cases, the D_2O is partially cooled by D_2O being returned to the HTS, and partially cooled by cooling water. Fig. 3.20 shows the purification system arrangement for systems operating at reduced pressure. Fig. 3.21 shows the purification system arrangement for systems operating at full HTS pressure.

Flow

In stations where the purification is performed at a reduced pressure, the flow is adjusted by varying the bias on the bleed valves. A typical maximum attainable flow is 40 kg/s, with a range of 8-10 kg/s being usual flow rate. Assuming IX column performance is normal, this will result in a cleanup half-life of about 3-4 hours. This is the time taken to reduce impurity levels to one-half of the original value, assuming no further impurity addition.

Increased flow rates can be selected, for example, to reduce levels of I^{131} in the HTS or to reduce the effects of crud releases. Resin may be damaged by excessive flow rates.

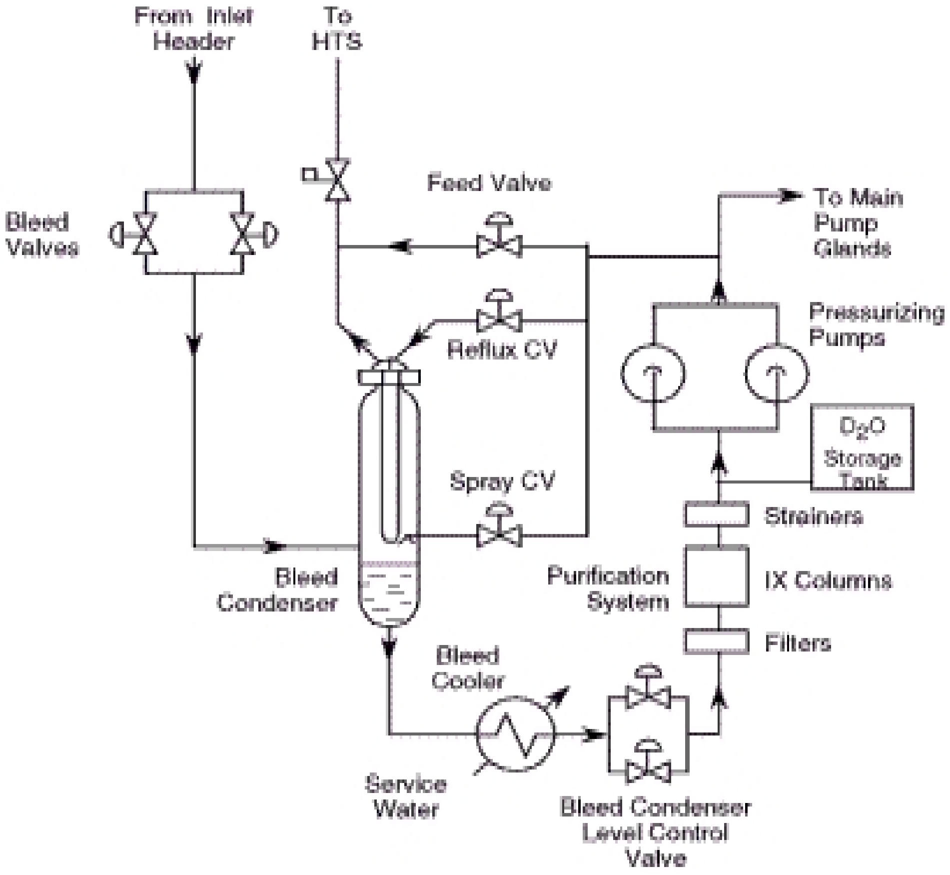


Figure 3.20
Purification System Requiring Pressure Reduction

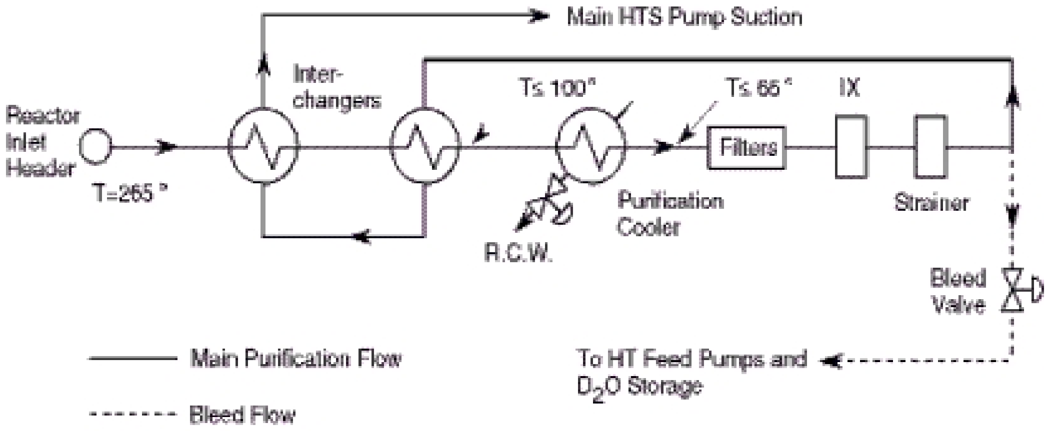


Figure 3.21
Purification System Using Full System Pressure

If this circulating crud is not removed from the HTS, subsequent neutron activation and re-deposition will create radiological problems in the HTS (increased man-rem). An increased purification flow will remove much or all of these products. But, the removal of these materials in the purification circuit will result in high radiation fields around the filters, strainers and IX columns.

However, purification flows that are too high will reduce IX column efficiency (coolant does not have enough time in the column to effectively exchange ions).

For stations where the purification operates at full HTS pressure, the purification circuit flow rate is independent of the bleed valve position. Purification is achieved via a bypass flow around the main HTS circulating pumps (refer back to Fig. 3.21). The operator manually controls the flow rate through the purification system by means of a flow control valve. Flow is controlled at an upper limit of ~25 kg/s, equivalent to a purification half-life of ~60 minutes.

Note that for the stations where the purification system operates at full HTS pressure, the HT system and circulating pump characteristics fix the purification pressure drop. Maximum flows are determined by pipe sizes and orifice plates, and are monitored by ΔP transmitters.

The purification flow control can be overridden by any high temperature situation, which may cause resin damage.

3.5.2 Purification ΔP

The filters, IX columns, and strainers are each provided with a differential pressure indicator (as shown in Fig. 3.19). Any increase in ΔP across the components will indicate a reduction of purification flow. This could impair the effectiveness of the purification system. For this reason it is important that any increase in ΔP above specifications be corrected.

For the filters, ΔP indicates the degree of crud accumulation and the need for filter replacement.

A high ΔP across the IX columns indicates an accumulation of solid impurities in the column or compaction of resin fines such that resin replacement may be required.

Strainers downstream of the IX columns will collect any IX resin that escapes. A high ΔP across the strainers indicates that strainer cleaning is required.

Inlet Pressure

Design flow through the purification circuit is achieved by setting a predetermined inlet pressure to cover all expected pressure drops in the system. Inlet pressure that is too high will result in increased purification flow through the IX column with a probable reduction in IX column efficiency. In addition, component overpressure may result (for systems operating at reduced pressures). This situation may be corrected by either:

a) Bypassing the purification system and flowing directly to D_2O storage

or

b) Pressure relief valves on the individual components. These will relieve to D_2O storage.

An inlet pressure that is too low will reduce purification flow. Again, this poses a risk of insufficient quantity of HTS D_2O being cleaned.

3.5.3 Abnormal Operating Conditions

We have already mentioned in passing that some situations require an increased purification flow, i.e. reducing radioiodines and reducing effects of crud releases. These situations will now be explained.

Removal Of Radioiodines

The station licence sets limits for the quantity of radioiodine that may be present in the HTS with the unit at power. The reason for the limit is to protect the public and station employees from exceeding regulatory dose limits, should a release from the HTS occur. The presence of radioiodines in the HTS indicates fuel has failed in the reactor. Purification flow is increased to remove the radioiodine. If the radioiodine levels exceed those stated in the licence, the unit must be shutdown. Even in the shutdown state, the purification flow will be maintained at a high level to facilitate the removal process. Note that the release of radioiodines from failed fuel may continue even after shutdown, depending on the severity of the fuel failure.

Crud Removal

Crud releases (crud-bursts) can occur during certain reactor operating conditions resulting from thermal or chemical transients, such as HTS warm-up and cooldown, reactor power maneuvering or during normal reactor operation when chemical parameters stray from specification.

In these instances, primary removal will be by filters and increased purification. The increase in purification will usually be achieved by either (or a combination of):

i) Increased purification flow (limited capability)

ii) Place more purification equipment in-service. This would increase the time spent in the IX columns by the coolant (i.e. for a given flow, the flow would move slower through a larger number of flow paths.

3.5.4 Summary Of The Key Concepts

- The HTS Purification System is designed to maintain HTS chemical parameters within specification and remove impurities from the HTS.
- Purification system temperatures are maintained $\leq$ 65°C to:
    - Ensure IX column resins do not release chemicals that could cause stress corrosion of reactor components
    - Prevent resin bead melting and migration into the HTS
    - Prevent a reduction in IX resin efficiency
- Proper cooling of the bleed flow controls the purification temperature. In the typical purification system, pressure and temperature reduction occurs in the bleed condenser and the bleed cooler. For the stations where the purification system operates at full HTS pressure, two interchangers and a purification cooler perform the cooling.
- Purification flow must be maintained at a sufficient rate to ensure crud and fission products (I^{131}) are removed. Without purification, this crud could be activated and could re-deposit within the HTS.
- The flow through purification may be controlled by the bleed bias. In stations where the purification system operates at full HTS pressure, the flow is manually controlled.

- High ΔP in the purification components would indicate that:
    - Filters are plugged and require replacement or
    - Strainers are plugged and require cleaning or
    - Resins are compacted or contaminated with impurities and will possibly require replacement
- The pressure at the inlet is set to overcome all expected loses in the purification system. An inlet pressure that is too high will result in excess purification flow and a corresponding decrease in resin efficiency. An inlet pressure that is too low will result in an insufficient purification flow for HTS cleanup.
- A control valve is provided to control purification inlet pressure below a maximum value by bypassing purification flow when its lift setpoint is exceeded. In addition, pressure relief valves are provided on individual components to protect them against overpressure.
- HTS warm-up/cooldown, reactor power maneuvres or normal operation with chemical excursions can cause crud bursts. Crud bursts are addressed by increasing purification flow or valving more purification equipment into service.

3.5.5 Heat Transport Hydrogen Addition System

Radiolysis of the HTS coolant while in the reactor core occurs with the resultant formation of D_2 and O_2 gases. These gases will remain in solution under normal HTS operating temperatures and pressures. Nonetheless, D_2 and O_2 can become liberated under certain operating conditions resulting in formation of explosive mixtures.

Fortunately, the radiolysis reaction is reversible. Recombination can be promoted by the addition of H_2 or D_2 gas, D_2 and H_2 will behave identically as far as the reaction is concerned. Either could be used to scavenge the oxygen; the only difference being the end product: D_2O or H_2O.

The choice of gas is mainly economic: hydrogen is much cheaper to buy than deuterium. However, the additional expense of D_2O downgrading must be considered since the addition of H_2 forms H_2O. At the moment hydrogen is used exclusively.

Hydrogen is added to the HTS to maintain the deuterium/hydrogen concentration; and hence the oxygen concentration, within station specified limits.

The hydrogen concentration is monitored (as opposed to oxygen) because of the ease of measuring H_2. This ensures that an optimum amount of H_2 is injected into the system.

Inappropriate addition of hydrogen can result in the following adverse consequences:

a) Insufficient addition of hydrogen will result in the presence of excess O_2. Excess O_2 will promote corrosion with subsequent component wastage and activated crud (corrosion product) formation.

b) Excessive addition of hydrogen is also undesirable since it promotes embrittlement of the pressure tubes . Note also that any corrosion would result in some excess of D_2 (H_2) .

There is a danger of H_2 coming out of solution at reduced HTS pressure (degassing).

Under normal operating conditions, degassing will be generally confined to two areas:

- The D_2O Storage Tank
- The Bleed Condenser (or Degasser Condenser, depending on the station)

Both have D_2O liquid in thermal equilibrium with the D_2O vapour above.

In the D_2O storage tank the cover gas is helium. But H_2/D_2 gas will also be present due to degassing of these radiolysis gases. A concentration of more than about 4% H_2/D_2 gas will require purging to reduce the possibility of an H_2/D_2 explosion.

The saturated vapour in the bleed condenser cover gas contains O_2, D_2/H_2 and fission product gases (such as Xe and Kr). These gases come out of solution from the HT D_2O when it flashes to steam upon entering the bleed condenser. Being non-condensable at the bleed condenser temperature, these gases accumulate gradually in the bleed condenser atmosphere. They concentrate mainly in the vicinity of the reflux cooling coils because that's where the vapour condenses and leaves the gases behind (a process referred to as tube blanketing). This collection of gases inhibits reflux cooling in the bleed condenser.

The partial pressure of vapour around the coils is lower than the partial pressure of vapour in the rest of the bleed condenser. Therefore, the condensed liquid that is formed on the cooling coils is cooler than the vapour at the D_2O inlet to the bleed condenser (where gas concentration is lower). Thus, the ΔT between the vapour at the condenser top and the liquid at the bottom is indicative of accumulation of gases. If the ΔT becomes excessive, degassing is accomplished by the off-gas management system. Degassing will remove fission product gases as well as D_2 and O_2 produced by radiolysis.

In units without bleed condensers, degassing is performed in the degasser condenser. A degassing flow is established to the degasser condenser from the HTS or by pressurizer steam bleed flow. The vapour/gas mixture is directed to a vent condenser, then to vapour recovery. Hence, the problem of reflux cooling capacity reduction is eliminated.

In a system that uses a degassing condenser there is only spray cooling. There are no reflux tubes in the condenser.

Reactor Shutdown

Radiolysis under shutdown conditions is minimal. Therefore, hydrogen addition is discontinued. This also reduces the risk of H_2 buildup in the HTS, especially during maintenance, when H_2 could create an explosion hazard. To further reduce this risk, H_2 addition may be halted a day before a planned shutdown occurs.

Hydrogen Supplies

The hydrogen injection supply is from standard hydrogen cylinders. In most stations, the hydrogen addition is located at the HT feed pump suction. Cylinders are declared spent when their pressure falls to suction pressure at the feed pumps. Since pumps can become gas-locked, the hydrogen supplies must be isolated when the pumps are shut down.

Note also that conventional hazards exist due to handling of pressurized gas cylinders and because H_2 can create an explosive mixture in air.

3.5.6 Summary Of The Key Concepts

- The addition of hydrogen to the HTS through the hydrogen addition system reverses the radiolysis reaction and recombines O_2 (to form H_2O) thus reducing risk of corrosion in the HT system. This system is not required during shutdowns, when radiolysis is much less.

- Increased amounts of non-condensible gases (mainly O_2, D_2 or H_2 and noble gases) in the bleed condenser cause reduced efficiency of reflux cooling. Increased concentrations of O_2 with D_2 or H_2 in the D_2O storage tank could result in an explosion hazard.

- Excess hydrogen addition to the HTS increases the risk of hydrogen embrittlement of pressure tubes.

3.5.7 Heat Transport Gland Seal Supply System

The main HTS pumps circulate hot (265°C), pressurized (~8-10 MPa) D_2O continuously, while the reactor is at power. Remember this D_2O contains radioactive materials. It is important that this D_2O be contained within the pump body and gland (which are part of the HTS boundary) at all times. To achieve this containment, the pump is sealed along its shaft through a gland.

This gland incorporates a number of mechanical seals (two or three depending on station). This seal arrangement allows a gradual pressure drop (from HTS pressure to atmospheric) in steps across the seals, hence reducing the pressure drop across the seals (i.e. causing some fluid to pass through each seal), a cooling and lubricating D_2O supply is available for the seal. It must also be noted that each of the primary or secondary seals is capable of holding full HTS pressure, but if one fails, redundancy has been lost.

For effective operation these seals must be continuously supplied with cool, pure, high-pressure D_2O. This is accomplished by the gland seal supply system.

This supply system has two main purposes:

a) To provide a flow of cool (~ 40°C), filtered D_2O to the gland for cooling and lubrication of the mechanical seals.

b) To provide high-pressure (~12 MPa) D_2O to the seal cavities, and thus prevent hot, unfiltered HT D_2O from entering the gland.

A representative gland seal and supply system is shown in Fig. 3.22.

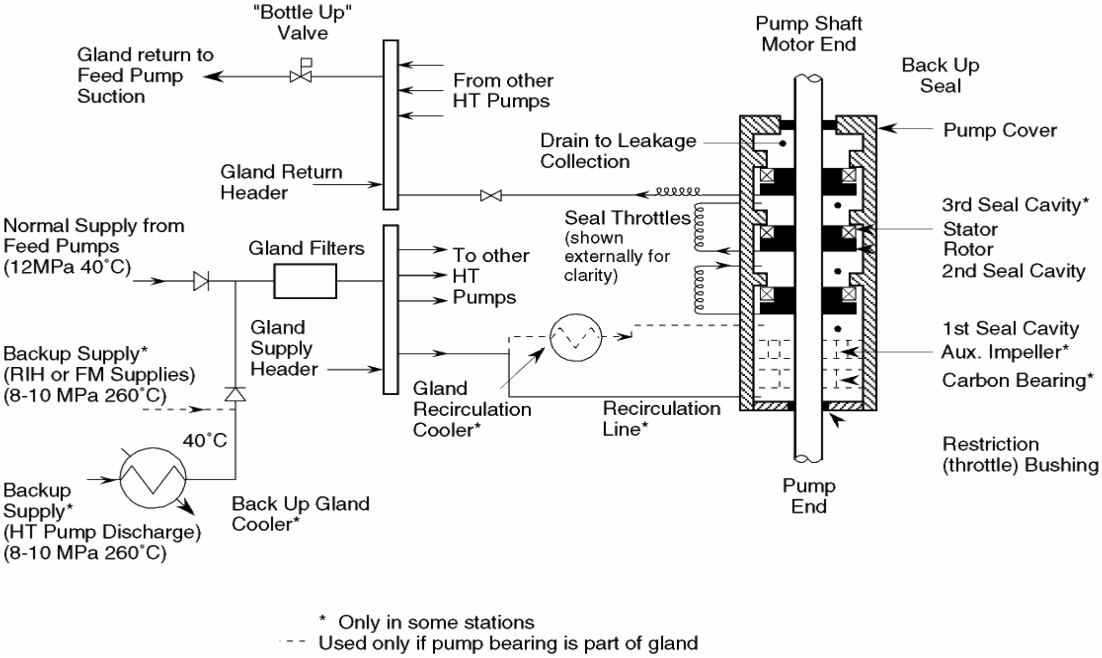


Figure 3.22
Typical Gland Seal

The normal supply of D_2O for the gland seal supply system is the D_2O storage tank. This D_2O has already passed through the HTS purification system. It is fed by the HTS feed pumps, via a filter system, to a gland supply header.

This bank of filters, under normal conditions, is a precautionary measure. It further reduces the possibility of abrasive particulates entering the gland. Note that the seal faces (carbon and tungsten carbide) are lapped to a high degree of flatness (thousandths of a millimeter) and even minute particles are capable of inflicting damage and, therefore, causing additional leakage through the seal faces.

A minimal amount of D_2O passes through each seal itself providing lubrication. This lubrication flow reduces any heat generated by friction. This flow will typically be a few cc/minute.

About 10% of the total gland supply D_2O flows between the various seal cavities via seal throttles (or breakdown cells) arranged in parallel with the seal faces. This results in a progressive lowering of D_2O pressure in successive seal cavities. The flow of this cool D_2O from cavity to cavity, via the breakdown cells, will also remove heat from the seal.

The remainder of the flow is handled in one of two ways, depending on the seal design. In some seals, all of the remaining flow (~90% of total flow) will enter the HTS through the restriction (throttle) bushing. This flow is the major factor preventing hot D_2O from the HTS entering the gland and also represents a constant addition of D_2O to the HTS inventory (i.e. bleed valve opening required). In other seal designs, only ~10% of the flow enters the HTS via the restriction bushing (serving the same purpose as mentioned above) and the rest of the flow goes into the recirculation flow in the seal. Note that a majority of this recirculation flow will bypass the seal through ports in the seal housing (not shown in Fig. 3.22).

Gland return flow is taken from the final seal cavity. Any leakage across the final seal will be contained by the backup seal and will be directed to D_2O collection.

As previously mentioned, the gland seal requires a supply of cool pressurized D_2O at all times when the HTS is at pressure. The loss of this supply would cause rapid overheating of the seal because of:

a) Loss of cool D_2O flowing through the seals.

b) Entry of hot D_2O from HTS through the restriction bushing.

This overheating can fail seals in a very short time period (typically minutes if the gland seal valve is not closed). To guard against this, a backup gland seal supply is provided. It is taken from the main HTS pump discharge (or RIH) and/or the fueling machine D_2O supply pumps (only in some stations). This will usually be at a high temperature (>250°C) and some cooling must be provided to cool the D_2O to ~40°C. This cooling is accomplished by either the recirculation cooler or by the backup gland cooler, depending on the seal design. This D_2O also has a higher level of impurities. The in-line gland filters are used to clean up the D_2O. This is the primary purpose of the gland filters.

Provision of check valves ensures that the backup supply becomes available immediately on loss of normal supply. The cooling water to the backup coolers or recirculation coolers (depending on the station) is always in-service. The check valves also prevent interaction between the backup and normal supply under normal conditions as the backup supply is at lower pressure.

Since a total loss of seal supply can cause seals to fail in a very short time, it is important to provide control room staff with indications of gland supply problems. These indications include:

a) Individual pump gland seal flow.

b) Gland return temperature

c) Gland interseal temperatures (and recirculation temperature, where used)

d) Gland interseal pressures

Gland filter differential pressure can also be monitored, which may indicate impending flow problems due to filter blockage. This could prevent potential seal damage.

No reactor or HT pump trips are directly initiated from these parameters. Manual intervention by the operator is required to trip the pump or adjust parameter values on alarms that require action.

Gland Return

The return lines from each gland return the D_2O to the feed pump suction. Seal cavity pressure can often be adjusted by manual operation of a valve in the return line.

The motorized bottle-up valve can be closed automatically on low gland supply flow. This may be necessary if, for example, feed pumps are lost and backup supplies are not available. This prevents the much hotter and impure HTS D_2O from entering the gland through the throttle bushing.

When bottled-up, cooling of gland seal water is now limited to that provided by the recirculation cooler (where installed) or by the cooling water jacket which surrounds the gland (not shown on diagram). Normal gland flow must be restored as soon as possible to avoid seal damage.

Summary Of The Key Concepts

- The HTS Gland Seal Supply System must be available at all times to keep the potentially contaminated HTS D_2O within the main pumps (hence within the HTS boundary).

- The HTS Gland Seal Supply System provides clean, cool, high pressure D_2O to the HTS pump glands. This provides cooling and lubrication for the mechanical seals and prevents leakage of the hot, impure HTS D_2O from the main HTS pump bodies from entering the gland. Filtering is required to ensure seal faces are not damaged by foreign particles.

- The backup gland seal supply is supplied from the discharge of the HTS circulating pumps (or RIH) and/or the fueling machine D_2O supply pumps. This water is hot and impure, hence it requires cooling and filtering before it is supplied to the gland.

- The seal flows, return temperatures, inter-seal temperatures (and also recirculation temperature) and inter-seal pressures can be monitored to determine seal condition.

- The bottle-up valve automatically closes on loss of seal flow. This prevents the hotter and impure HTS D_2O from flowing through the seal.

3.6 ASSIGNMENT

3.6.1 Heat Transfer.

1. For each of the operating states listed below, draw & label the power flow block diagram that show the role of the HTS in transporting heat energy.

   a) At full power, with rated electrical output to the grid (two major pathways),

   b) During poison prevent (major pathway only), for a station using CSDV's and for a station using SRV's.

      The labels must show:
      - i Major heat source
      - ii Heat Carriers,
      - iii Required pumps,
      - iv Heat energy transfer points,
      - v Heat sinks.

2. Explain the two operation constraints on the operation of the HTS system for the prevention of delayed hydride cracking.

3. Explain three broad categories of potential hazards associated with the HTS:

4. Hydrogen gas is added to the HTS system. Explain 2 hazards that this creates.

3.6.2 Pressure and Inventory Control.

5. During operation the pressure in the HTS is maintained between upper and lower limits. Explain the possible consequences of operating outside the limits.

6. Give two reasons why coolant flow blockages are a major concern.

7. State three effects of boiling in a fuel channel.

8. Explain why some boiling is allowed in some CANDU reactors.

9. Explain why it is necessary to have pressure and inventory control.

10. State five purposes of the feed and bleed system for a unit with a pressurizer when it is the solid mode of operation.

11. State five purposes of the feed and bleed system for a unit with a pressurizer when it is in normal mode of operation.

12. State the purpose of the pressurizer in the normal mode of operation.

13. Briefly explain the changes in the pressure and inventory control system in normal mode if the pressure in the system is

    a. Higher than set point.

    b. Lower than set point.

14. State six purposes of the feed and bleed system in a station with no pressurizer.

15. State and explain three reasons why the level in the pressurizer is controlled.

16. Explain how shrink and swell are accommodate, in a unit with a pressurizer, during temperature changes between cold and zero power hot.

17. Explain 2 ways feed and bleed requirements are minimized in stations not using a pressurizer.

18. Explain two purposes of the D_2O transfer system.

19. Explain three purposes of the D_2O storage tank.

20. Explain two reasons for a lower limit on D_2O storage tank level

21. Explain two reasons for an upper limit on D_2O storage tank level.

22. Explain how the pressure is controlled in a bleed condenser.

23. Explain how pressure is controlled in a degasser condenser.

24. For HT systems with and without pressurizers, indicate on the following table, where applicable, the response of pressurizer levels, feed and bleed flows, HTS pressure and temperature, feed/bleed response and boiler pressure for a reactor power increase.

	Units with Pressurizer	Units without Pressurizer
HTS Pressure		
HTS Avg. Temperature		
Boiler Pressure		
Feed and Bleed Action		
Pressurizer Level		

25. State the reason for over pressure relief of the HTS.

26. Explain the two major cause of HTS over-pressurization.

27. Define the terms direct and indirect pressurize reduction.

28. Explain two methods of direct pressure reduction.

29. Explain how indirect pressure reduction is accomplished.

30. Explain how the size of the HTS liquid relief valves is determined.

31. Describe the major effects of the following process upsets:

    a. failed open pressure relief valve (liquid relief valve),

    b. feed pump failure,

    c. steam bleed valve fails open,

    d. failure of a main HTS pump

3.6.3 Shutdown Cooling

32. Explain the difference between direct and indirect types of shutdown cooling.

33. Explain the operation of a direct shutdown cooling system.

34. Explain the operation of an indirect shutdown cooling system.

35. Explain the operation of a shutdown cooling system that has both a shutdown and maintenance cooling system

36. Explain how thermosyphoning is achieved.

37. State the four conditions required to maintain thermosyphoning.

38. Define the terms

    a. Crash cool down

    b. Emergency cool down

39. Describe the likely constraints on using the shutdown cooling system at full heat transport system temperatures.

3.6.4 Heavy Water

40. State two reasons why there is a minimum limit on the isotopic of the HTS.

41. State one reason why there is a maximum limit on the HTS.

42. List 4 major causes of downgrading of the HTS.

43. On the following table, indicate the effect of HT system downgrading:

	Short-Term Effects	Long-Term Effects
HTS Downgrading To The Limits Specified in OP&Ps		
HTS Downgrading To Below The Limits Specified in OP&Ps		

44. List four major radiological hazards of the HTS when the reactor is shutdown.

45. List two additional radiological hazards when the reactor is operating at high power levels.

46. Explain the purpose(s) of each of the following collection systems.

    a. HT D_2O collection

    b. Miscellaneous D2O collection

    c. Vapour Recovery System (4)

    d. Liquid Recovery System

49. Explain why the water in the miscellaneous collection system is kept separate from the HT collection system.

50. State three adverse consequences of a high D2O collection rate.

51. Explain the danger associated with a pressure tube leak.

52. State three consequences of a boiler tube leak.

53. Explain why water returned from the collection system must be free of contaminants.

3.6.5 Heat Transport System Auxiliaries

54. Give three reasons why the temperature of purification flow must be controlled.

55. Describe how cooling of purification flow is accomplished in stations with reduced pressure purification systems.

56. Describe how cooling of the purification flow is accomplished in stations with full pressure purification.

57. Describe the problems is the purification flow rate is too high or too low.

58. Explain why ΔP across the purification system in monitored.

59. State three reasons for ensuring the pressure at the inlet to the purification system is correct.

60. Give two ways in which a high pressure can be corrected.

61. State two HTS conditions that might require an increase in impurity removal rate.

62. State two methods for increasing impurity removal rate.

63. State the purpose of the hydrogen addition system.

64. Explain the consequences of the H_2 concentration in the HTS exceeding either its high or low limit.

65. Explain the consequence of H_2, D_2, and O_2 coming out of solution in the bleed condenser.

66. Explain the consequence of H_2, D_2, and O_2 coming out of solution in the D_2O storage

67. State the two major purpose of the gland sealing supply system.

68. Explain why the gland seal supply must be cooled, filtered and pressurized.

69. State the source of the back up supply for the gland seal supply system.

70. State 4 parameters that are monitored to verify the condition of the gland seal.

4 Special Safety Systems

4.1 *Shutdown Systems*

The purpose of the shutdown systems (SDS) is to quickly shut down the reactor by a rapid insertion of large amounts of negative reactivity into the core. This may be required during major process system failures that cannot be safely handled by the Reactor Regulating System (RRS), stepback or setback functions, or other safety related systems.

4.1.1 Effectiveness of Shutdown Systems

The shutdown systems must be capable of responding to the worst unit failure or combination of failures and safely shutdown the reactor to a level that will maintain cooling capability to the fuel. For example, a large LOCA will cause a large increase in reactivity due to voiding of fuel channels. This will produce a large increase in reactor power

It will also reduce heat sink effectiveness by reducing HTS system pressure. A Loss of Regulation Accident (LORA) can cause a fast increase in reactivity, and consequently a fast rise in reactor power. The shutdown systems must be capable of responding both quickly enough and with enough negative reactivity depth to prevent failure of the coolant system boundary following a process system failure.

The trip setpoints chosen reflect parameters to prevent fuel melting and subsequent failure. Since we don’t have operational experience with fuel centerline melting, we cannot say, with any confidence, that pressure tube failure will not occur if centerline melting occurs. Hence, fuel centerline melting dictates the choice of setpoints for the trip parameters. The only way we can be reasonably sure that centerline melting will not occur is to prevent dryout.

Let us consider another problem. If heat production is greater than heat removal, should the reactor be tripped or should the power be brought down through a setback in order to restore heat balance? The key to answering this question is time and size of heat imbalance. Typically, a reactor trip will bring the reactor power down to ~6-7% FP in a few seconds while a setback at a typical rate of 0.5%/sec will do the same thing in ~3.5 minutes. It is clear that we cannot afford a serious imbalance in heat production versus heat removal for ~3.5 minutes. Therefore, the reactor must be tripped.

The shutdown systems must insert a larger amount of negative reactivity faster than the positive reactivity buildup created by the unit failure.

Both SDS1 and SDS2 are typically actuated in less than one second and that in less than two seconds enough negative reactivity is inserted to terminate any failures.

4.1.2 Types of Shutdown Systems

In CANDU reactors three types of shutdown systems have been used: shutoff rods, liquid poison injection, dump tank. In new reactors built in the 1980s reactors have two shutdown system. shutoff rods, poison injection. Reactors built prior to these used dump tanks as their method of shutdown.

Shut-Off Rods (SORs)

Stainless steel encased, hollow cadmium (a strong neutron absorber) rods drop, under gravity, into the core. Vertical guide tubes are located within the calandria to guide the rods while they fall into the core. These rods are normally held above the core by electrically energized clutches, located on the reactivity mechanism deck. When this shutdown system is actuated, the clutches holding the rods above the core de-energize (channelized electrical contacts), allowing the rods to fall into the core (the initial acceleration is assisted by springs, which are compressed by the retracted rods). This makes the reactor deeply subcritical, and thus, reactor power drops quickly to a low level.

Liquid Poison Injection

The liquid injection shutdown system operates by injection of gadolinium nitrate solution, under pressure, through horizontal dispersion lines into the moderator. Gadolinium, is a strong neutron absorber. This system consists of several gadolinium nitrate (poison) tanks, which can have their contents driven into the core by pressurized helium. When this shutdown system is actuated, helium pressure is applied to the poison tanks through channelized valves. The poison is then displaced and distributed into the moderator, causing the same effect as the SORs, a rapid drop in power to a low level.

Dump Tank

A few early CANDU units use moderator dump to provide a shutdown. This is accomplished by dumping the moderator into a separate dump tank below the calandria. With the moderator out of the calandria, the fast fission neutrons are not slowed or thermalized, hence, reactor power drops to a safe, low level.

Because of its relatively slow action time, moderator dump is not a primary method of achieving a shutdown. It will only be used if the shut-off rods do not reduce reactor power quickly enough.

4.1.3 Recovery from Shutdown System Trip

It is possible to quickly reset the shutoff rod trip (if the cause of the trip is known and corrected), thus avoiding a poison outage. Recovery immediately after a liquid poison injection trip is impossible, due to the length of time required for the moderator purification system to remove the poison. This is why the SOR trip (SDS1) is the preferred SDS and is actuated first.

4.1.4 Safety Design Principles

In order to prevent faults in one safety system from affecting another system, the shutdown systems are functionally independent from:

- Each other
- The reactor regulating system
- Any process system, for example, SDS1 uses power to cause the contacts to open, SDS2 uses air actuated valves to cause the poison injection
- The other safety related systems (ECIS, containment)

Each SDS is independent from the other in two aspects:

1. Functional independence is achieved by designing the two shutdown systems on two different principles: mechanical insertion of a strong neutron absorber and chemical poisoning of the moderator by a neutron absorber.

2. Geometric independence is achieved by the vertical insertion of shut-off rods while the liquid poison is injected through horizontal tubes into the core.

Fail-Safe Feature

We have to ensure that the shutdown systems are fail-safe. This means that, in the event of equipment, power or other failures of the shutdown systems, they will shut down the reactor (even though it may not be the result of an actual trip). This assures that reactor power will be reduced if the shutdown system fails. Fail-safe, in this case, means that failure of a component or channel will cause the device(s) to go to the position that they would go to if the system tripped.

For example, in the case of SDS1, the SORs are held above the core by energized clutches. If a power failure to the clutches occurs, the clutches are de-energized and the SORs drop into the core shutting down the reactor.

In the case of SDS2, helium under pressure is isolated from the poison storage tanks by pneumatically actuated air-to-close valves. If an instrument air failure occurs, and the valve actuator loses pressure, the valves will open. The pressurized helium will then drive the poison from the storage tanks into the core, shutting down the reactor. Air reservoirs connected to the actuators fill to instrument air system pressure via a non-return valve. The non-return valve prevents the air in the reservoir from re-entering the failed air system. A loss of air supply will not automatically cause a trip, since the stored air will keep the valve in its closed position. Also note that a genuine trip will dump the air in a normal manner.

This fail-safe feature cannot accommodate all failures. Examples of failures that cannot be guarded against are helium injection valves sticking closed or SOR being stuck out of the core. These types of failures are not annunciated and would be detected by safety system tests. This illustrates one reason why we perform tests on these passive systems.

Interlocks

When a shutdown system trips the reactor, the reactor regulating system is signaled and will not attempt to raise power levels. It will also take the following additional safety steps to augment the trip:

- Fill the liquid zones
- Drop control absorbers (CA) into the core
- Lower the reactor power setpoint

The main purpose of these additional safety steps is to ensure that the reactor regulating system is supporting the actions of the shutdown system. In addition, CA insertion prevents the reactor from going critical on withdrawal of the SORs when the trip is reset.

While the reactor is tripped, interlocks prevent the removal of moderator poison and the driving out of control absorbers and adjuster rods. This prevents an inadvertent reactivity increase.

The interlock restrictions remain in force until the shutdown systems are functional again (poised).

Absolute and Conditional Trips

Reactor trips are of two types:

1. Absolute
2. Conditional

An absolute trip is a trip that is functional at all states of reactor power.

Log Rate is an absolute trip. Its trip value for SDS1 is set at 10% Present Power

(PP)/second at any power. If the reactor power increase is too fast to be safely handled by the reactor regulating system, the shutdown systems will trip the reactor.

Further examples of absolute trips are:

- High Neutron Power provides protection against fuel overrating at all times.
- Heat Transport High Pressure provides protection against HT overpressure and damage resulting in a LOCA.

A conditional trip is valid only above a certain power limit. Conditional trips allow the unit to be shutdown without tripping the reactor, keeping the shutdown system poised for use. Depending on the parameter, these trips can be conditioned out at different levels.

The conditional trips also protect against reactor power increases from low power by being reactivated at the conditioning level. As reactor power increases, the trip conditioning parameter will be met at the appropriate power level and will trip the reactor preventing any further power increases.

For example, low HT pressure is a conditional trip. This low HT pressure trip protects against dryout at high power conditions (ie prevent film boiling/dryout). During a reactor shutdown and cooldown, HT pressure can be lowered. As reactor power is lowered to below the conditioning level, the low HT pressure trip is conditioned out. This prevents an unwanted reactor trip. At low power levels, the fuel will be cold, and dryout is less likely to occur. At the lower HT pressure, reactor safety is not compromised because heat removal capability from the fuel is not impaired. But say that the reactor power increases unexpectedly from the low power state with low HT pressure. At powers above the conditioning level, boiling and dryout may occur in the HT system as the fuel temperature increases. The power increase would cause the reactor to trip when power reached the trip conditioning level, preventing dryout.

Another example of a conditional trip is heat transport gross coolant low flow. For example, the trip setpoint for this variable is typically set between 75% and 90% nominal flow, provided the reactor power is greater than ~1% FP. If reactor power is below ~1% FP, then this trip is conditioned out. Full coolant circulation is not required to remove this heat (alternate heat sinks have this capacity).

Even with the reduced circulation, dryout will not occur, since the fuel is cold. This conditioning trip allows the main HT pumps to be shut down during a unit shutdown. An increase in reactor power above the conditioning level without adequate coolant circulation would cause the reactor to trip, preventing dryout.

Further examples of conditional trips are:

- Boiler Low Level,
- Pressurizer Low Level.

Trip Protection

Key neutronic and process system variables are monitored at all times. These unit variables have trip setpoints. When the key unit variables exceed the trip setpoints on two of three channels, the shutdown system is actuated and will trip the reactor.

Shutdown system trip setpoints for SDS1 and SDS2 are staggered to allow SDS1 to trip first, thus making a trip recovery possible (discussed in the staggering of trip setpoints section).

Although the exact set of trip parameters varies from station to station, the most common key variables are listed on the next couple of pages.

1. High Neutron Power

The trip value is set below the level at which the fuel bundle power ratings (critical channel power) would be exceeded. This prevents excessive power increases resulting from a large LOCA (where channel voiding has taken place) or during a LORA (where the rate is low enough to not trip on neutronic rate and not increase HTS pressure beyond the pressure and inventory control capabilities).

2. Neutronic Rate (Log or Linear)

Prevents the reactor power from increasing so fast that RRS is unable to effectively limit the peak power reached (loss of reactor control). This could occur during a large LOCA as mentioned above or during a fast LORA.

3. Heat Transport Pressure High

This trip is used to protect against excessive overpressurization of HT system due to the loss of heat sink effectiveness. This also protects against accidents like a slow (or moderate) LORA (pressure and inventory control system cannot accommodate swell), loss of feedwater, and loss of Class IV power.

4. Heat Transport Pressure Low

Primarily installed to cope with the effects of LOCAs and steamline breaks which cause a rapid collapse of HTS pressure. This trip prevents critical channel power from decreasing due to a decrease in HT pressure. This will prevent dryout and the resultant fuel overheating and failure.

5. Heat Transport Gross Coolant Low Flow

Trip variable used to cope with the effects of LOCAs and loss of Class IV power where pump trip results in reduced HTS circulation. Low flow trip prevents the critical channel power from decreasing due to a decrease in HT coolant flow. This will prevent dryout and the resultant fuel overheating and failure.

6. Pressurizer Low Level

Addresses effects of accidents causing a shortage of HT D_2O inventory, like LOCAs or steamline breaks (causing coolant shrinkage and pressure reduction, see also HT low pressure trip).

7. Boiler Low Level

   Addresses effects of failures in the steam and feedwater system, i.e., steam line breaks and feedwater breaks. This parameter trips the reactor if the boilers are lost (or anticipated to be lost) as a heat sink.

8. Boiler Feedwater Low Pressure

   Responds to failures in the feedwater system (feed line breaks, pump failures, etc.). This parameter trips the reactor if the boilers are lost (or anticipated to be lost) as a heat sink.

9. Moderator Temperature High

   Responds to loss of moderator heat sink. In stations using boosters, high booster coolant (moderator) temperature will trip the reactor to prevent booster damage.

10. Reactor Building High Pressure

    Addresses effects of a LOCA or feedwater/steam line break inside containment.

11. Heat Transport High Temperature

    Responds to fuel overheating and HTS overpressure protection as a backup for a loss of heat sink effectiveness (non-boiling reactors only).

Redundant Parameters

The unit has many combinations of possible trip parameters:

For excessive heat production (beyond the capacity of heat sinks),

- Neutronic rate
- High neutron power

For mismatch between heat production and heat removal,

- Heat transport pressure high

- Heat transport temperature high

Impending mismatches are protected by:

- Boiler low level
- Boiler Feed line Low Pressure
- Moderator Temperature High ensures that heat balance is maintained in the moderator

For loss or impending loss of HT system,

- Heat transport gross coolant low flow
- Boiler room pressure high
- HT low pressure
- Pressurizer low level

The point to make here is that, for the same unit failure, the unit has a combination of trip protections. Should one or more trip protections fail, others will shut down the reactor. Those redundant parameters are an important design feature, which contribute considerably to the safety CANDU reactors.

As an example, a combination of effects/trip protections for a LOCA could be:

a) Voiding in the pressure tubes. This causes a steep rise in reactor power due to positive void reactivity coefficient. Neutronic rate and high neutron power trips provide protection.

b) Depressurization of HT system due to loss of D_2O coolant. Heat transport pressure low trip provides protection.

c) Increasing boiler room pressure. The HT system D_2O, escaping at high pressure and temperature flashes into steam causing an increase in pressure. Boiler room high-pressure trip is available.

d) Decrease in the coolant flow if an inlet header should rupture. D_2O designated for channel flow would be lost from the break. Heat transport gross coolant low flow trip is available.

e) Decreasing level in the pressurizer through the loss of HT system D_2O. Pressurizer level low trip is available.

Staggering of Trip Set points

Note also that the trip set points are staggered for SDS1 and SDS2 to avoid actuation of both systems in the same time. This keeps the SDS2 poised and ready to fire, should SDS1 fail to lower reactor power. Also, a recovery from a trip is possible with SDS1 if the cause of the trip can be identified and corrected quickly. With SDS2 we do not have this option because poison removal from the moderator takes too long. Therefore, once SDS2 has fired, a poison outage cannot be avoided.

For an example of the above, typically the RATE LOG trip value is set at 10% PP/second for SDS1 and 15% PP/second for SDS2.

Manual Trips

If the operator has reason has to believe that a serious unit failure has occurred and an automatic trip has failed, the reactor must be tripped manually even if an automatic trip has not occurred (yet). This is an extra safety feature added to CANDU reactors.

4.1.5 Summary Of The Key Concepts

- The shutdown systems protect against loss of reactor control and loss of heat sink effectiveness.

- The shutdown system must insert enough reactivity depth quickly enough to counteract any unit failure or combination of failures to prevent coolant system boundary failures. The shutdown system must be a fail-safe system to trip the reactor should any component or energy supply for the system fail.

- The purpose of interlocks with shutdown systems is to prevent inadvertent reactivity increases.

- An absolute trip parameter is a trip parameter that is valid at all levels of reactor operation. A conditional trip parameter is only valid above a certain reactor power level. This allows the shutdown system to remain poised (its desired state) during a shutdown.

- A fast LORA will cause the reactor to trip on neutronic rate. rate parameter was chosen because the rapid power increase will be detected and will trip the reactor.

- A slow LORA will trip the reactor on high neutron power and/or high heat transport pressure (depending on the rate of power increase). If reactor power increases cause a large HTS swell as heat input is increased, the HTS pressure will increase. If the reactor power increase is slow enough to keep the pressure increase within the capacity of the pressure and inventory control system the reactor power will rise to the high neutron power trip setpoint.

- A loss of heat sink effectiveness will trip the reactor on high heat transport pressure or high ht temperature. These parameters have been chosen because the reduction in heat sink effectiveness will cause the HTS temperature to increase, causing an immediate swell in the HTS. The boiler low level trips and boiler feedwater low pressure will also protect against the reduction of heat sink capability (as backup trip parameters).

- Redundant parameters ensure that the reactor trips even if a trip parameter should fail. This is an additional safety feature for the shutdown system design.

- For enhanced reactor safety, the reactor is to be tripped manually if the operator believes that a serious unit failure has occurred, even if the reactor has not tripped on its own.

4.2 Emergency Coolant Injection

This section will cover the purpose of the ECIS system, its initiation and operation. A typical system is shown in Fig. 4.1.

4.2.1 Purpose Of The ECIS

The Emergency Coolant Injection System (ECIS) is an integral part of the defence in depth philosophy which governs the operation of CANDU reactors. Recall that this philosophy considers the presence of five separate barriers designed to minimize the release of fission products to the environment. These are:

- Ceramic Fuel,

- Fuel Sheath,
- Pressure Tube,
- Containment,
- Exclusion Zone.

The ECI system is poised with the unit in a normal operational state. It will automatically operate to cool the heat transport system in the event of a loss of coolant accident. A flow of light water is injected to refill the HT system, re-wet the fuel and provide a heat sink for any residual and decay heat.

Note for large breaks, the coolant discharged from the break will be sufficient to carry heat from the fuel (although the boilers are still the primary heat sink). In the case of smaller breaks, where the discharge of coolant is not sufficient to cool the fuel, alternate methods of heat removal must be used (i.e., in the boilers by maintaining coolant circulation as long as possible).

The amount of fission products released from the fuel after a LOCA will depend on the size of the LOCA and how well ECIS has performed. When ECIS is fully functional and able to cope with a LOCA, a large number of fuel failures are not expected.

If for any reason the automatic operation of ECIS fails, the operator can intervene at any point in the sequence of operations and manually initiate ECI.

4.2.2 Loss Of Coolant Accident (LOCA)

A LOCA is defined as a leak of D_2O from the HT system causing sustained low HT pressure. This would mean that normal HT pressure cannot be maintained or pressure recovery to normal levels is not anticipated within a defined time, usually five to ten minutes.

Examples of a loss of coolant (LOCA) from the HT system could be:

- A header break
- A pressure tube or feeder break
- Failure of an ice plug while the system is open for maintenance during a shutdown

During a shutdown LOCA is detected by a loss of D_2O inventory by a loss of HT inventory.

4.2.3 Support System Requirements

Effective operation of the ECIS must follow operation of either or both Shutdown Systems (SDSs). On large LOCAs, the leak will cause the HT pressure to fall, which will cause the coolant in the HTS to flash to steam (voiding). The void coefficient results in a large positive reactivity increase and a rapid rise in reactor power. The reactor regulating system tries to control this power increase, but is not designed to handle such rapid insertions of positive reactivity. Consequently, there will be an automatic shutdown of the reactor by SDS1 and/or SDS2 initiated by a log rate and/or high neutron power trip.

For smaller LOCAs (rupture of a small feeder or instrument line), the loss of HT inventory will be slow enough that the regulating system can cope with the resultant power increases.

Under these conditions, the reactor trip will be initiated by non-neutronic trips, such as low HT pressure or low pressurizer level.

For the larger LOCAs, the resultant rise in reactor vault pressure due to the escaping coolant flashing to steam will cause features of the containment system to come into operation. This action further reduces the risk of large quantities of radioactive fission products being released to the environment. This issue will be discussed further in the section on containment.

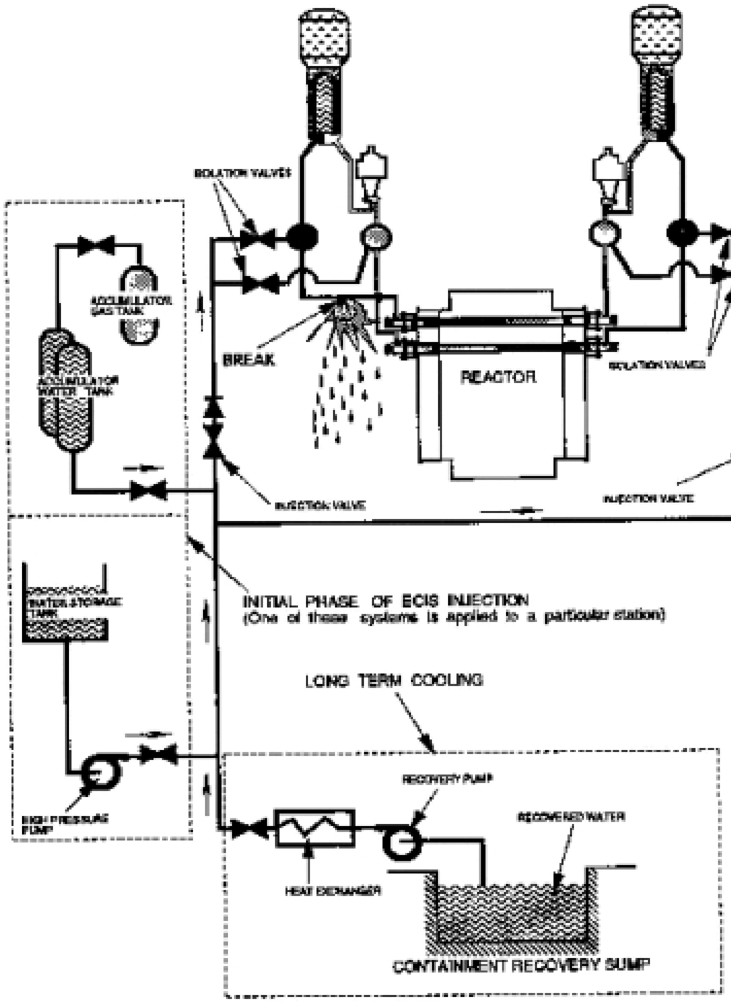


Figure 4.1 - Simplified ECI System

Note 1: Either pumped or gas driven injection, not both

Note 2: Number and position of valves vary with location and state of the system. Position of valves will not be shown.

4.2.4 ECI System Initiation

The ECI system will automatically operate when a majority vote (2 out of 3, 3 out of 4 channels, depending on the station) is received in the primary and at least one conditioning parameter (which are also channelized). For all CANDU stations, the primary parameter is low

HT system pressure. The pressure (typically ~5 MPa) is well below the HT pressure that would cause a reactor trip (typically 7 to 8 MPa).

The conditioning parameter distinguishes the event as a LOCA, as opposed to a process failure. For example, low HT pressure can be caused by a loss of HT feed, but low HT pressure in conjunction with rising vault pressure could indicate that a loss of coolant is occurring to the vault.

The conditioning parameters in use vary with the station, but may include high vault temperature or high vault/boiler room pressure, high moderator level (for LOCA into the moderator) sustained low HT pressure and low HT flow.

4.2.5 ECI System Phases

There are three principal operational phases: blowdown,, injection, recovery.

Blowdown

Once the reactor has tripped, the primary requirement is to provide an alternate source of cooling water to the fuel (now approaching decay heat levels) as quickly as possible. ECIS injection can only commence when the HT system pressure has fallen to the ECIS injection setpoint. This depressurizing period is typically referred to as blowdown. Initially, a HT pressure reduction occurs due to the leak and due to the shrinkage of D_2O after a reactor trip. The rate of depressurization will slow down as the pressure in the HTS reaches the saturation pressure associated with the HTS temperature. At this pressure, the coolant flashes to steam to prevent total collapse of HTS pressure. The time taken for this to occur is largely dependent upon the size of the LOCA, hence, blowdown times can vary greatly.

Once ECIS is initiated, a crash cooldown of the boilers is initiated. All boiler safety valves (or large steam reject valves, in some stations) are opened to reduce boiler pressure (hence boiler temperature) causing HTS shrinkage. This further lowering of HTS pressure will allow the colder ECI water to enter the reactor and will also reduce the leakage rate of inventory from the HT system. This effectively removes the boilers as a heat source, which could maintain HT pressure and temperature, hence slowing the depressurization. (Once the cold ECI water is injected into the HTS, its main purpose is to cool the fuel. If cold water is injected without crash cooling, the hot feedwater in the boilers will transfer heat to the injected water and the HTS). This is especially useful for small LOCAs, when the depressurization of the HTS can be slow. This allows cold ECIS water to be injected sooner.

The main HT pumps maintain circulation through the HT system for as long as possible. A higher flow rate of coolant from the core to the boilers is achieved with these pumps running. This results in a higher rate of heat removal from the heat transport system and hence, faster depressurization to injection pressure. Forced circulation also mixes liquid and vapour (retarding vapour pocket formation) which aids in keeping the fuel wet, thus minimizing fuel failures. The pumping of two-phase flow and/or pump cavitation due to low suction pressure will cause severe vibrations in the HT circulation pumps. To prevent further loss of inventory due to pump seal damage, the pumps may have to be tripped (in some stations the failed pump seals will cause a breach of containment).

As mentioned for thermosyphoning, the inertia of the main HTS pump motors or flywheels will continue circulating the coolant for some time after the pumps are tripped (but may be opposed by ECIS injection).

In some stations, low speed drives are installed on main HT pumps, which continue circulation of the coolant to maintain fuel cooling. These low speed drives will allow the pump to operate without cavitation. This is especially useful for small breaks, where the discharge of the coolant from the break is not sufficient to carry heat from the fuel (as mentioned earlier in this module).

Injection

At the ECIS injection pressure, injection of water into the system commences to restore coolant inventory. This is referred to as the injection phase. Light water injection from one or more storage tank(s) continues until the inventory from the tank(s) has been depleted. The injection phase can vary in duration, depending on the break size and the water inventory available.

High-pressure injection is accomplished by one of two methods. Some stations use high-pressure pumps to inject the light water coolant to the core. The other stations use a pressurized gas (N_2) to drive the injection water into the core.

At some stations, a grade elevation water tank and/or an elevated emergency water storage tank (part of the dousing tank reserved for injection) exists to supplement the inventory of water available for injection. Once the high-pressure injection phase is over, low pressure pumped injection begins from these tanks. This extra water is particularly useful in bridging the period between the high-pressure injection and the recovery phase.

Typical high-pressure ECIS injection pressures range between 4.2 and 5.5 MPa depending on the station and delivery method used.

This range of injection pressures is chosen for three main reasons:

a) The extra system cost needed to provide equivalent flow at higher pressure (particularly for a pump system) is not warranted.

b) To reduce the amount of time and number of occasions that the ECIS must be blocked when operating at reduced HT pressures.

c) To reduce water hammer effects.

Point (b) is important since one of the logic decisions required for injection is to determine if the HT pressure is less than ECIS injection pressure.

The system size and injection pressure is optimized to provide adequate injection flow and pressure before the HT inventory has been depleted. This prevents fuel failures that may occur during blowdown.

Recovery

HT system blowdown and ECIS injection cause potentially vast quantities of light and heavy water mixture to discharge from the break. This water is collected in the ECI recovery sumps in the containment floor. It is then cooled in heat exchangers and re-injected into the HT system by recovery pumps (or in some stations, to the suction of the HP injection pumps). This is referred to as the recovery phase (or post accident water cooling, in some stations). In most stations this is accomplished by a dedicated recovery system. This maintains adequate cooling in the HT system and provides a long-term heat sink for the reactor to prevent fuel failures (due to overheating from decay heat).

The heat removal mechanism from decay heat levels is shown in Fig. 4.2

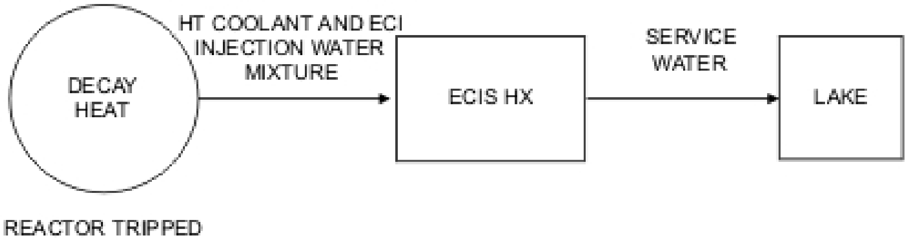


Figure 4.1 - ECIS Heat Removal Chain

The quantity of water injected during the HP and LP injection phases must be sufficient to accommodate water lost due to holdup in the recovery flow path. It must also provide sufficient recovery pump suction head to prevent cavitation and possible vapour locking of the recovery pumps. Water recovered from the recovery sumps must be screened and filtered to prevent debris from blocking the pump inlets and thereby impairing the recovery phase. For this reason, housekeeping inside the reactor vaults is very important.

The recovery pumps do not require the higher pressure (and flow) delivery capability of the injection phase since the HT system is operating at reduced pressure. Also, the decay heat produced by the reactor is substantially reduced in the long term. The recovery system is therefore sized accordingly, for long-term performance with reduced flow and pressure requirements.

The duration of the recovery phase can be up to three months. For this reason, it is important that there is a secure electrical supply to the recovery pumps. Therefore, Class III power is used.

4.2.6 ECIS System Operation

Note that the ECI system in an individual station may vary from the system(s) described below. The intent is to generically describe the actions of a typical ECI system. Any differences will be discussed in your station specific training.

Once the ECI initiation pressure is reached and at least one conditioning parameter is satisfied, the following major actions occur simultaneously:

- Crash cooldown, which was discussed earlier in the module
- Preparation for HP injection (and LP pumped injection)
- Preparation for the recovery phase of system operation

For systems using gas accumulators, fast acting valves open to allow the pressurized gas in the accumulators to pressurize the water held in the accumulator water storage tanks. The unit H_2O and D_2O injection valve will open in the affected unit only to allow injection flow to commence. ECIS valve sequence and operation are designed to minimize the effects of water hammer, which could be caused by the rapid injection of water (i.e. valves open slowly, system is vented to remove air gaps, etc.). Injection will continue until a low level in the accumulator water storage tank is reached. The isolation valves will then close to prevent gas ingress into the HT system. The recovery pumps are also started when ECI is initiated, in preparation for the recovery flow.

For systems using high-pressure water pumps, water in the ECI storage tank(s) feed the suction of these pumps. These pumps are started when ECI is initiated (or when conditioning parameter is satisfied, depending on the station), in preparation for the injection flow.

The recovery pumps are also started and will recirculate injection water. The unit H_2O and D_2O injection valves will open (in the affected unit only) to allow injection flow to commence (water hammer preventive measures are as mentioned above). Injection will continue until a low level in the water storage tank is reached (or in some stations, a preset time limit is exceeded). The isolation valves close to prevent air ingress into the pumps and ECI system.

In some stations, after the initial high-pressure injection is completed, grade level or emergency water storage tanks provide additional water. The valves from the tank open and recovery pumps discharge this water into the reactor core. This phase continues until a preset low level in the tank is reached or a preset high level in the recovery sump is reached. This ensures adequate water is available for the recovery phase. The storage tank isolation valves will then close.

Once the above injections are completed, the recovery phase (post-accident water cooling) begins. Water that has spilled from the reactor has been collected in the recovery sump. The recovery sump isolation valves will then open and the recovery flow will start. Water will be pumped from the recovery sump to the recovery heat exchangers. Then the water is returned to the reactor core for fuel cooling. In the recovery heat exchangers, the reactor decay heat is transferred to cooling water.

4.2.7 Emergency Coolant Injection System Reliability

Like the two shutdown systems, high reliability is maintained by ensuring independence, redundancy and selection of high quality components for construction and maintenance of the system.

4.2.8 Emergency Coolant Injection System States

Let us consider the following states of readiness in which the ECIS can exist: poised, blocked, recallable.

Poised

While poised, the system is available to operate automatically when the initiatingn parameter setpoints are reached on the correct number of channels. No operator action is required.

Blocked

When blocked, the system will not operate automatically. When the heat transport main system is being depressurized, automatic injection is prevented by a blocking handswitch, which overrides the automatic opening of the injection control valve(s). This prevents an initiation when heat transport pressure drops below ECI injection pressure. The result of injection would be addition of H_2O and downgrading of the HT heavy water which would result in a considerable economic penalty.

However, blocking of ECIS is only permissible once heat transport temperature is below specified value (typically <90°C) or when HT pressure is at or below injection pressure (this must be performed before ECI conditioning parameters are satisfied). A blocked system needs only simple control room action to return it to the poised state.

When the heat transport system is depressurized for maintenance and ECI is blocked, ECI can be manually initiated in the event of a LOCA. Recall also that if for any reason the automatic operation of ECIS fails, the operator can manually initiate ECI.

Recallable

The system will not operate automatically or manually.

The ECI system can only be made recallable with the unit(s) in a specified shutdown and cooldown state. It must always be possible to restore it to service within a predefined time that depends upon the status of the unit, and is specified in your station operating manual.

4.2.9 Summary Of The Key Concepts

- The purpose of the ECI system is to provide a heat sink for the fuel in the event of a LOCA to protect the first two barriers to fission product release.

- A loss of coolant accident (LOCA) is defined as a leak of D_2O from the HTS causing sustained low pressure.

- SDS trip parameters for large LOCAs are neutronic trips. SDS trip parameters for small LOCAs are low pressure or low pressurizer level.

- Containment system actions will be required for a LOCA into containment.

- The major ECI initiating parameter for a LOCA will be low HTS pressure combined with at least one conditioning parameter. Typical conditioning parameters are high reactor vault temperatures and pressures, boiler room high pressure, high moderator level, low HT flow and sustained low HT pressure.

- The blowdown phase of ECI is the phase that allows the HTS to depressurize to ECI injection pressure.

- The injection phase is the period where injection of stored water takes place.

- The recovery phase is the period that the water recovered from the LOCA is cooled and re-injected (via pumps) into the reactor to maintain long-term fuel cooling.

- ECI initiates a crash cooldown to remove the boilers as a heat source. This reduces the leakage rate from the HTS. This also ensures pressure reduces to allow injection of cold water into the HTS for fuel cooling.

- HTS coolant circulation is maintained as long as possible to maximize coolant circulation for fuel cooling. This results in a higher rate of heat transfer to the boilers and ensures that depressurization to ECI injection pressure will occur as fast as possible. The flow of coolant also mixes liquids and vapors to prevent vapour pocket formation, hence keeping fuel wet.

- For systems using gas accumulators, fast acting valves open to allow the pressurized gas in the accumulators to pressurize the water held in the accumulator water storage tanks. For systems using high pressure water pumps, valves open to allow the water in the ECI storage tank(s) to feed the suction of these pumps. The pumps are started in preparation for the injection flow.

- The unit H_2O and D_2O injection valves will open (in the affected unit only) to allow injection flow to commence.

- In some stations, after the initial high pressure injection is completed, additional water is provided by other storage tanks. The recovery pumps discharge this water into the reactor core.

- Once the above injections are completed, the recovery phase (post accident water cooling) begins. Water that has spilled from the reactor has been collected in the recovery sump. The recovery sump isolation valves will open and the recovery flow will start. Water will be taken from the recovery sump, pumped to the recovery heat exchangers and then the water is returned to the reactor core for fuel cooling. The recovery heat exchangers will remove the decay heat from the coolant.

- The reliability of the ECI system is increased by the use of:

    - Redundant components

    - Quality components

    - Independence

- The term poised refers to the state when ECI is ready to operate automatically, in the event of a LOCA.

- The term blocked refers to the prevention of the system from operating automatically as designed. In this state the system can be returned to service (i.e. poised) by simple control room action.

- The ECI system can also be fired manually in case :

    - A LOCA occurs while depressurized for maintenance (i.e. while blocked)

  - Automatic actions do not occur as designed (i.e. while poised)

- The term recallable refers to a state when the system cannot be activated manually or automatically. While in this state, the system must be able to be returned to service within a predetermined time limit.

- The HTS must be below a certain temperature (typically 90°C) before the ECI system can be blocked.

- If the HTS is depressurized before the ECI system is blocked, ECI will operate as designed when conditioning parameters are met. This would downgrade the HTS, resulting in a severe economic penalty.

4.3 Containment

The containment system protects the public, station personnel and equipment against the adverse conditions following an increase in reactor building pressure, usually as a result of a LOCA. This module will discuss the types of containment systems, the types of containment structures, the function and operation of containment components.

The containment system is designed to contain:

a) The energy released as heat and pressure

b) The activity released, e.g. tritium and fission products to within limits

The LOCA, which usually triggers the use of the containment system, may have been caused by such events as:

a) Mechanical failure of the HTS, for example, as a result of long term poor chemical control or a system transient

b) Loss of Regulation Accident (LORA) with failure to shut down the reactor quickly enough with subsequent pressure tube failure

c) Loss of Class IV power with failure to shut down the unit, again, followed by pressure tube failure

For events such as (b) and (c) to occur, both shutdown systems must fail (such a combination of failures highly unlikely). Due to failure to shutdown the reactor, the amount of energy released to containment under these two circumstances would be much higher than that from a LOCA in which reactor power is terminated by shutdown system action.

Let’s review the events following a LOCA into containment at full power. The Heat Transport System (HTS) D_2O at high pressure and temperature will be released, and a portion of it will flash to steam. The reactor building temperature and pressure will increase. Pressure may be above atmospheric for a few minutes, whereas temperature may rise to as high as 95°C for several hours.

The containment structure must provide the initial heat sink under these conditions until alternate long term heat sinks can be made available (e.g. ECIS Recovery Heat Exchangers) following ECIS operation to rewet and cool the fuel.

The amount of fission products released will depend on how rapidly the power pulse was terminated, how the fuel was operating prior to the LOCA and how well the ECIS has performed. When the ECIS is fully functional and copes with the LOCA, a large number of fuel failures are unlikely, and the quantity of fission products released will be small. Remember, the primary function of ECIS is to maintain fuel cooling, which will prevent/minimize fuel failures following a LOCA. However, a LOCA can cause tritium releases in the reactor building in the order of tens of thousands of times the maximum permissible concentration in air (MPCa).

If for any reason ECIS is unable to fully cope with the LOCA, a large number of fuel failures are almost certain and a large release of fission products is to be expected. Higher than normal radiation fields will occur inside containment.

Containment is basically a structural envelope that contains the reactor and high-pressure components of the HTS. At various locations interfacing with other systems will occur, i.e. boilers. The interfacing depends on how much equipment is located within containment.

In earlier CANDU stations and at 600 MW units, all boilers and HTS circulating pumps are totally within containment. This naturally increases the size of the reactor buildings required to house these components.

In the case of the older CANDU units, a larger containment structure is required to accommodate the larger volume of the reactor vaults.

At newer stations, the decision was made, following a detailed safety study, to relocate various equipment items and thereby reduce the size of containment required. For example, only the main HT pump bowls and boiler bases are within containment. Fig. 4.3 shows the extension of the HTS beyond the containment boundary.

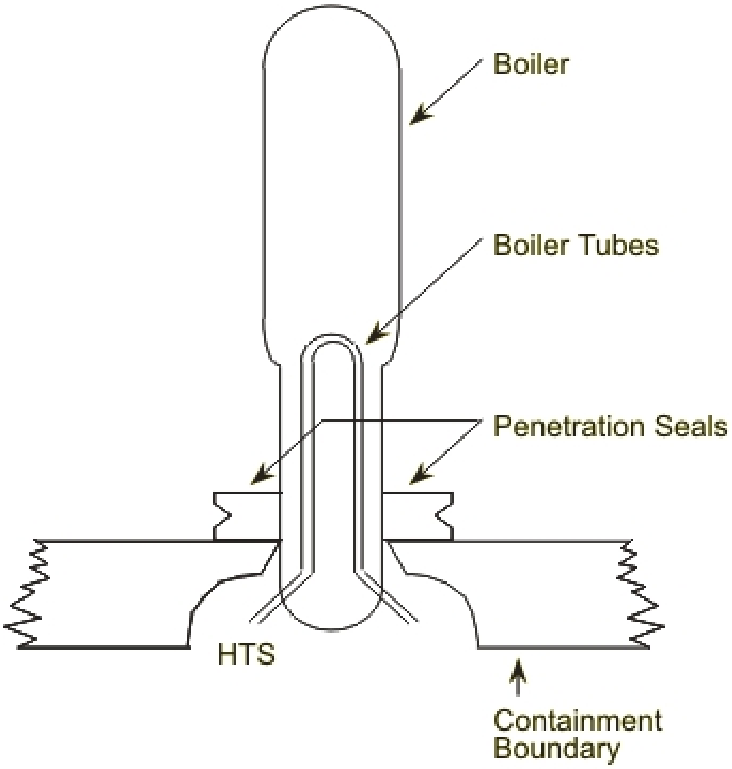


Figure 4.3 - Typical Boiler Configuration

The larger containment structure of older stations has areas that have some accessibility on. Depending on anticipated hazards, these areas may or may not be under access control. This feature is not present at the newer stations.

Containment effectiveness is determined by the leak rate from the structure during an accident situation. The basic principle is, therefore, to eliminate or minimize leaks and, if leakage occurs, it must be in a controlled manner and monitored. This is one reason why containment is maintained subatmospheric. Any leakage is inward. An exhaust flow is maintained to keep the pressure subatmospheric. This exhaust is filtered and monitored.

Note that all containment penetrations (piping, cables, airlocks, transfer chambers, etc.) have seals to prevent leakage. A periodic pressure test is also performed to verify containment integrity.

Outleakage will occur if containment pressure is above atmospheric. If pressure exceeds design limits, containment structural damage can occur.

4.3.1 TYPES OF CONTAINMENT

Two types of containment systems are currently employed in CANDU reactors:

1. Pressure suppression - used in CANDU 600 MW single unit stations.

2. Negative pressure - used at all Ontario Hydro multi-unit stations.

The effectiveness of both types of containment is dependent upon having a poised ECI system available to limit the longer term energy input in the event of a LOCA.

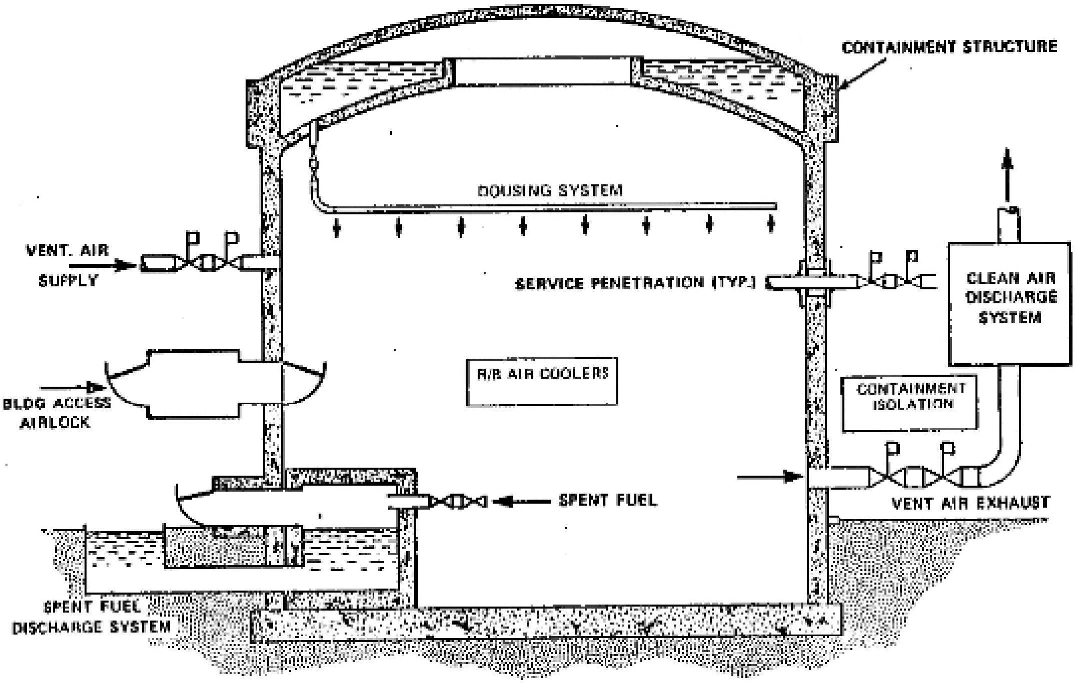


Figure 4.4 - Typical Pressure Suppression Containment System

4.3.2 Pressure Suppression Containment (PSC)

A general schematic of a pressure suppression system is shown in Fig. 4.4.

Containment consists of a prestressed concrete structure with a domed roof, a dousing system, airlocks and a closure system. The concrete walls are over one (1) meter thick.

All internal surfaces of the containment structure including: upper dome, outer walls, and base slab, the outer surfaces of the irradiated fuel discharge bay and airlocks, normally form part of the containment boundary. During fuel transfers, the boundary extends to the surfaces of the irradiated fuel storage bay.

During normal operation, the pressure within containment is maintained slightly subatmospheric by ventilation system operation.

When, for any reason, the containment pressure increases above atmospheric and especially during a LOCA, the leakage from containment must be limited. The release of tritium and fission products to the environment is kept below the maximum permissible level by not exceeding a specified leak rate. For any size of LOCA, the overpressure should not exceed the limit of ~120 kPa (g).

A dousing tank is located in the dome of the containment building. It holds light water for both dousing (~2000 m^3) and medium pressure emergency coolant injection (~500 m^3). Dousing is accomplished by the opening of the dousing valves. With these valves open, water flows by gravity from the storage tank to the spray headers to cause dousing. (These valves are channelized and require a majority vote to initiate dousing). Dousing condenses the released steam and thus:

1. Absorbs the heat energy in the steam
2. Reduces the magnitude and duration of the containment overpressure pulse
3. Dissolves soluble fission products (i.e. I^{131}), and entrains insoluble fission products, minimizing the airborne spread of contamination

Noble gas fission products, like Krypton 88, will be unaffected by dousing.

The containment structure is normally cooled and dehumidified by vault coolers. This is necessary due to sources of heat (HTS piping, boilers, etc.) and humidity (small leaks of D_2O, H_2O) within containment.

PSC Button-up/Box-up

During a LOCA, the containment structure can be isolated from the environment by closing the isolation points. The isolation points are dampers at the ventilation penetrations and valves on the piping penetrations. This is termed button-up or box-up and is done to prevent leakage above permissible levels (as discussed in the previous section).

Button-Up (Box-Up) is typically initiated by any of the following signals:

- High containment radioactivity,
- High containment pressure,

- High exhaust and stack radioactivity or loss of stack monitoring.

4.3.3 Operation of PSC during a Small LOCA

In the case of a small LOCA, the energy release will be smaller but will likely occur over a longer period. Containment pressure will slowly increase, and box-up will occur on one or more of the initiating parameters. The vault coolers may condense the resulting steam (and limit containment pressure) such that pressure to initiate dousing is not reached.

If pressure continues to rise to the dousing setpoint, (~14 kPa (g)), some intermittent dousing action will occur as the dousing valves open and close on staggered setpoints.

Under these conditions after the initial period of dousing, which will cease when pressure falls to the dousing OFF setpoint (~7 kPa (g)), pressure will probably again increase and further dousing cycles may be required until pressure remains below the OFF setpoint. As energy input from the LOCA falls (due to depressurization of the HTS), condensation on walls, and vault coolers becomes a major factor in keeping containment pressure low.

4.3.4 Operation of PSC during a Large LOCA

For a large LOCA containment pressure and temperature increase rapidly. Containment button-up (and a reactor trip) occurs at a containment pressure of about 3.5 kPa (g) and dousing commences at an overpressure of approximately 14 kPa(g).

For a large LOCA, a period of continuous dousing will quickly reduce containment pressure towards atmospheric. The vault cooling system and periods of dousing further reduce containment pressure as required. Once pressure has returned to near atmospheric, efforts can be made to clean up the containment atmosphere.

4.3.5 Summary Of The Key Concepts

- Two types of containment are pressure suppression containment and negative pressure containment. A poised system common to both is the ECI system.

- PSC pressure is normally maintained subatmospheric by the ventilation system.

- The dousing system limits containment pressure by condensing steam released as a result of a LOCA. Also, soluble and insoluble fission products will be dissolved/entrained in the water.

- Dousing, for a PSC system, will be initiated by high vault pressure and occurs via the opening of dousing valves, which are located in the distribution lines below the dousing tank.

- Box-up (button-up) is a means of isolating the containment structure from the environment. Ventilation and piping penetrations are closed to prevent leakage above permissible levels.

- Following a large LOCA, for a PSC system, containment pressure quickly starts to rise. Box-up (or button-up) is initiated on one or more of the initiating parameters. The dousing valves will open to initiate dousing to cope with the large pressure increase. As containment pressure reduces, dousing stops, but will restart as required to maintain pressure low.

- Following a small LOCA, for a PSC system, containment pressure slowly starts to rise. Box-up (or button-up) is initiated on one or more of the initiating parameters. The vault coolers will act to condense the steam and will cool the vault atmosphere. This may limit the containment pressure increase to the point where no dousing action is required. If containment pressure continues to rise, dousing will start and stop intermittently to keep containment pressure low.

- Vault coolers normally act to cool and dehumidify the containment atmosphere.

- The water in the dousing tank is for both dousing and ECI injection.

4.3.6 Negative Pressure Containment

This form of containment is used for all multi-unit CANDU stations, with some site variations.

The system is characterized by a vacuum building which, as its name suggests, is normally held at a pressure well below atmospheric, typically 7 to 14 kPa (a). The reactors themselves are housed in separate reinforced concrete buildings. The two structures are connected by a pressure relief duct, which allows any steam/air mixture in the event of a LOCA to travel to the vacuum building. The vacuum building (see Fig. 13.4) is normally isolated from the relief duct (more specifically, the pressure relief valve manifold) by a number of pressure relief valves.

The reactor buildings (and pressure relief duct) are normally maintained at a slightly subatmospheric pressure to minimize outleakage of potentially contaminated air during normal reactor operation (by purge driers, or ventilation systems , depending on the station).

At older stations containment is larger than at other sites. This dictates that the vacuum building must have a larger volume.

The vacuum building concept is unique to multi-line CANDU stations for which it offers an economical advantage over individual systems.

One disadvantage of a Negative Pressure Containment System (NPC) is that following a LOCA on a single unit, the vacuum building becomes unavailable to the other units, and shutdown of these unaffected units is required. Note also that the ECI is no longer available for injection to the other units, hence a shutdown would be required anyway.

Following a LOCA, the subsequent rise in pressure in the pressure relief duct will cause the pressure relief valves to open. The air and steam/contaminants produced by the LOCA are then drawn from the reactor vaults into the vacuum building. This means that the affected unit is purged of its contaminated atmosphere in a relatively short period (30-60 seconds). Containment pressure in the affected unit can return to subatmospheric once again. This minimizes both the contamination of equipment within the reactor building and any uncontrolled releases.

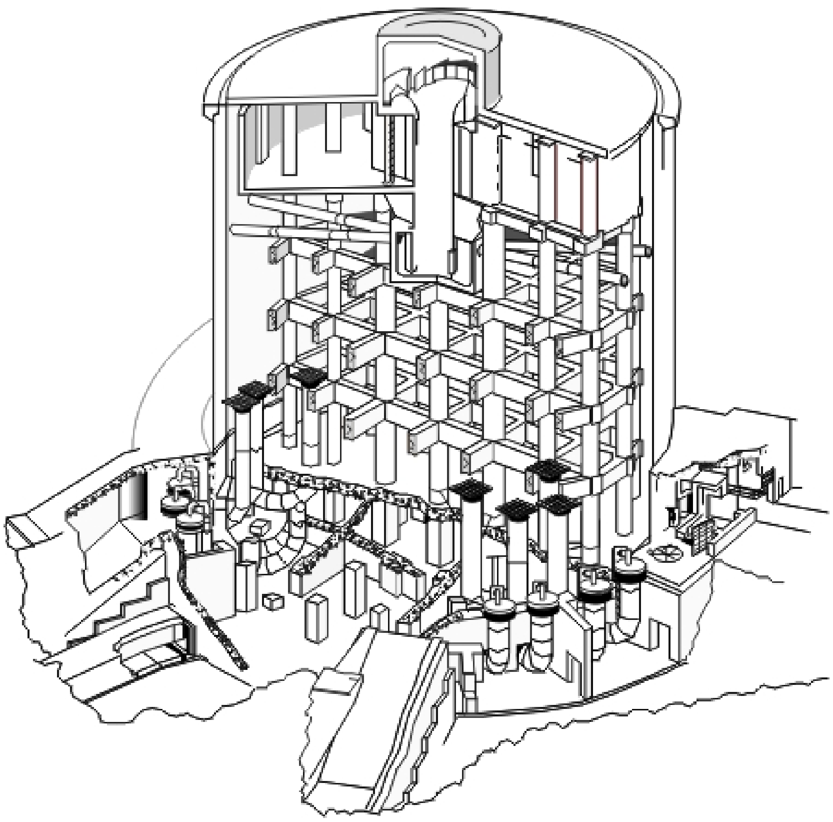


Figure 4.5: Typical Vacuum Building

One additional note to make here is that the requirement to remove the steam/air mixture from the reactor vaults requires a clear passage to the vacuum building. This is why the fueling machines should not be parked side-by-side in the fuelling machine duct (part of the pressure relief path to the vacuum building). Improper parking of the fueling machines with a LOCA in progress could restrict steam/air movement, which would allow pressure on the LOCA side of the fueling machines to build up. This could cause damage to the reactor vault due to overpressurization.

This containment structure will leak at a higher rate during the short overpressure during a LOCA. But, this is only short term. This is because NPC has a higher leak rate for short term whereas PSC has a lower leak rate, but for a longer time

Vacuum Building

The vacuum building greatly reduces the chance of leaks from the containment area, by limiting containment overpressure during a LOCA. Without it, even the short duration overpressure transient (30-60 seconds) in the containment area following a LOCA would result in unacceptable leakage to the environment.

The building is a reinforced concrete structure of sufficient volume to accommodate all of the air and steam drawn in from the reactor building and pressure relief duct in the event of an accident.

Note that the upper portion of the vacuum building contains an emergency water storage tank (see Fig 4.6) which contains water for both dousing and the ECIS (in some stations). This water also provides the necessary vacuum isolation between the upper and main chambers plus the water seal in the spray (or dousing) header.

The vacuum building is divided into:

a) Upper Vacuum Chamber

This chamber is isolated by watersealing and held at a low subatmospheric pressure, typically ~7 kPa(a), by means of vacuum pumps located in the vacuum building basement. Its main purpose is to provide a ΔP to automatically initiate dousing action following a LOCA.

b) Main Chamber

This has a much larger volume than the upper chamber (typically 60-70 times larger), and again, is maintained at a pressure of approximately ~7 kPa(a). This pressure is maintained by vacuum pumps, similar to those used for the upper chamber, which are also located in the vacuum building basement. Isolation from the upper chamber is by a water seal, and isolation from the containment structure is by the pressure relief valves.

The main vacuum chamber accommodates the steam-air mixture from a LOCA (or steam line break into containment). It is in this chamber that the dousing will occur. As noted for a PSC system, dousing condenses the steam, limits vacuum building pressure increases and dissolves and entrains fission products (except for noble gases).

Pressure Relief Valves

The pressure relief valves form the isolation between the pressure relief duct and the vacuum building. They are designed to open automatically when the pressure in the relief duct rises to just above atmospheric (typically at ~3.5-7 kPa (g)).

There are, typically, 12 to 20 such valves depending on the station. The majority are termed Pressure Relief Valves (PRV), and three or four, depending on the station, are Instrumented Pressure Relief Valves (IPRV). As the pressure rises in the pressure relief valve manifold (directly connected to the relief duct) to the required setpoint, the pressure acts directly on the PRVs and IPRVs, causing the valves to open. This will allow the high-pressure air-steam mixture to enter the vacuum building from containment.

When the pressure falls (typically to +3.5 kPa(g)), all PRVs will close while the IPRVs remain open until pressure falls to a subatmospheric level (-2 kPa(g)). The IPRVs will then modulate between an open and closed position as pressure varies in a range from -1 kPa (g) to -2 kPa(g).

The IPRVs can be manually controlled because the top of the valve can be subjected to a vacuum from the vacuum building, causing the valve to open.

At some stations, in addition to PRV's and IPRV's, there are Auxiliary Pressure Relief Valves (APRV) which are physically smaller, and are capable of handling the pressures generated by small LOCA's. Their operating setpoints are lower than those of the larger PRV's. Typically, they open at +1.5 kPa (g) and will reclose as pressure falls to about -6.5 kPa (g). They then will modulate as pressure varies between the closed value and -3.5 kPa (g) when they will once again be fully open.

Note that in the case of a large LOCA all PRVs, IPRVs, and any APRVs will open.

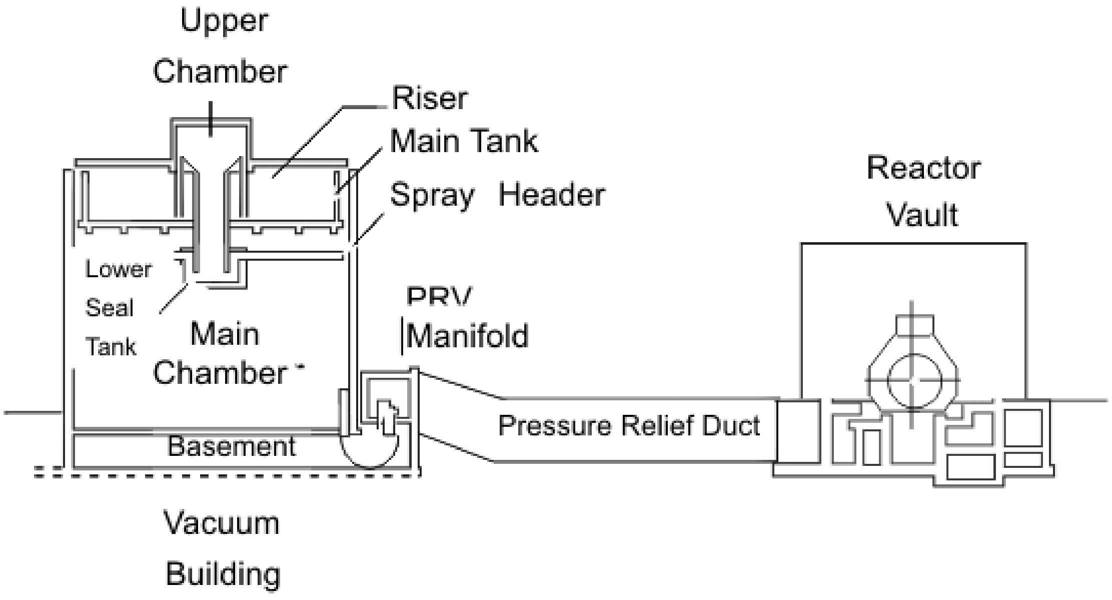


Figure 4.6
Schematic of Typical Negative Pressure Containment System

Vacuum Duct

The vacuum duct (or vacuum pipe) is the passage from the PRVs into the main vacuum chamber, allowing the air/steam mixtures following a LOCA to enter the vacuum building. From Fig 4.6 you will notice their shape, and hence the reason for their other name, J-Tubes.

Their shape serves another purpose. The duct allows isolation of a PRV from the vacuum building by filling the vacuum duct with water. The filling of the duct forms a water seal between containment and the vacuum building, allowing for maintenance/manual opening of the valve.

Note that the duct opening is well above, or extends well above, the main chamber floor. This prevents water on the floor (after a douse) from flooding these tubes and forming a water seal. Flooding of these tubes would make the vacuum building unavailable to keep containment pressure subatmospheric.

NPC Button-Up/Box-Up

The button-up/box-up method is similar to that previously mentioned for PSC systems, i.e. dampers and valves on penetration close. But for an NPC system, this will also automatically turn off all vacuum pumps for both upper and main vacuum chambers to prevent discharge of contaminated air.

Vault Cooling

As for a PSC system, the containment structure is cooled and dehumidified by vault coolers. This is necessary due to sources of heat (HTS piping, boilers, etc.) and humidity (small leaks of D_2O, H_2O) within containment. This system normally maintains containment between 35-40°C.

4.3.7 Summary Of The Key Concepts

- Vacuum pumps maintain the vacuum building upper and main chamber pressures at a very low level. This maintains the effectiveness of the vacuum building as an energy sink following a LOCA.

- The main chamber provides an area to which the reactor vault atmosphere is drawn following a LOCA. The steam will be condensed there by the dousing action as pressure increases.

- The upper chamber maintains a ΔP that allows an increase in main chamber pressure to automatically cause dousing.

- PRVs isolate the pressure relief duct from the vacuum building main vacuum chamber. These valves will open automatically to control containment pressure increases following a LOCA. Large and small PRVs actuate to cope with large LOCAs, by allowing a large amount of air/steam mixture to enter the vacuum building. After the pressure has been reduced, the small PRVs will modulate to maintain containment pressure subatmospheric in the longer term. Instrumented PRVs can be operated from the control room. This is accomplished by applying a vacuum to the top of the valve (from the vacuum building).

- The vacuum duct connects the pressure relief duct to the main vacuum chamber (isolated by the PRVs). This duct allows maintenance on a PRV, when the duct is filled with water, by forming a water seal.

- The pressure relief duct connects the reactor containment structures (vaults) to the pressure relief manifold.

- The upper chamber is isolated to maintain a ΔP from the lower chamber by a water seal. Vacuum is maintained by the vacuum pumps, which remove any air inleakage.
- The PRVs operate when containment pressure exceeds a design limit. Increasing pressure acting directly on the valve will cause the valve to lift off its seat.
- Box-up or button-up will be initiated by containment high pressure, containment high radioactivity, or stack monitoring high radioactivity/out of service. This action closes all potential leakage points out of the containment structure by closing valves, dampers, etc.
- Vault coolers normally provide cooling and dehumidification to containment.

4.3.8 NPC Operation during a Large LOCA

A large LOCA will generate large volumes of high temperature steam (~100°C) as the HTS coolant escapes from the break. Pressure and temperature within containment will quickly increase and initiate containment box-up (button-up).

As relief duct pressure increases to the design pressure of the PRVs (APRVs first, where installed, followed by the IPRVs and main PRVs), they will open, and the high pressure, high temperature air/steam mixture will be drawn into the vacuum building through the vacuum ducts.

The increase in vacuum building pressure acts on the water in the emergency storage tank and water is forced into the upper vacuum chamber. Note that the water seal prevents the main chamber atmosphere from entering the upper chamber (through the outlet header) as main chamber pressure increases. The filling of the upper chamber with water allows flow over a weir into the outlet and spray headers, thus initiating dousing into the main chamber. The spray of cold H_2O into the steam/air mixture (in the main chamber) will condense the steam. This will reduce pressure as the volume of the steam decreases.

Note that, in most stations, the weir design in the upper chamber (as shown in Fig 13.4) prevents the formation of syphon, by preventing the air in the upper chamber from being carried into the outlet header.

If the air in the upper chamber is lost, a syphon will form. If a syphon forms during dousing, it will not stop until the tank is empty.

As a result of the pressure decrease during dousing, PRV closure will occur. PRVs initially, then followed by APRVs and IPRVs. Containment pressure will then be maintained subatmospheric by the IPRVs or APRVs and vault coolers, as described earlier. A typical pressure transient for a large LOCA is shown in Fig. 4.7.

In the long term, to retain the containment pressure subatmospheric, the filtered air discharge system (FADs) is initiated by the operator.

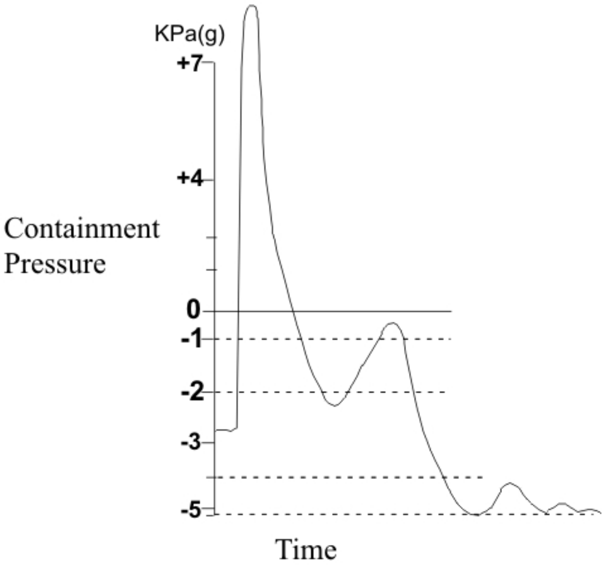


Figure 4.7
Typical Pressure Transient Following a LOCA

4.3.9 NPC Operation during a Small LOCA

In this instance, the pressure rise within containment will be smaller, and it is likely that the opening pressure of the large PRVs will not be reached.

In this instance IPRVs or APRVs will handle the overpressure in containment depending on the station. When containment pressure is reduced, the APRVs will close, but will modulate to maintain containment pressure negative. If the LOCA is small enough, the opening pressure of any relief valve may not be achieved, and the increase in pressure and the return to subatmospheric conditions will be handled by the vault coolers (provided enough steam is condensed).

Dousing during a small LOCA will be dependent upon the pressure rise in the vacuum building, and, if dousing occurs, it will cycle following the modulation of the IPRVs or APRVs.

4.3.10 Airlocks

Airlocks are penetrations in the containment boundary that are provided to allow the passage of personnel and equipment, without breaching the containment boundary. This is accomplished by the use of a double set of doors in each airlock. By having only one door open at any time, the containment boundary is not breached. Each of the airlock doors is sealed with an inflatable seal. Operating procedures and built in interlocks are used to ensure that the containment boundary is not breached when airlocks are used.

Larger penetrations, for the transfer of very large pieces of equipment are called transfer chambers. They are similar to an airlock, but are constructed of concrete, rather than steel. Their operation is also the same as an airlock, with a very few being sealed by bolted connections.

4.3.11 Filtered Air Discharge System

Following a LOCA event, containment will gradually repressurize due to air inleakage (small holes in containment seals, air system leakage, etc.) Filtered air discharge is initiated to keep containment or the vacuum building subatmospheric. Containment air is evacuated via the FAD (Filtered Air Discharge) system instead of via the normal operation filter (through the contaminated exhaust system). FAD consists of demisters (which remove entrained water droplets), heavy duty High Efficiency Particulate in Air (HEPA) filters to remove particulates and charcoal absorbers to remove radioiodines. Once the air discharge is established through FAD, the containment atmosphere can be maintained in a subatmospheric state (note that these FAD units are not 100% efficient, and will release small amounts of particulates and radioiodines, tritium and all the noble gas activity).

4.3.12 Hydrogen Igniters

In the event of a LOCA with a coincident failure of ECIS, high fuel sheath temperatures will result. If the fuel temperature exceeds ~1100°C, steam/zirconium oxidation will cause the formation of D_2/H_2 by the following reaction:

$$\mathrm{Zr} + 2\mathrm{D}_2 O \longrightarrow ZrO_2 + 2\mathrm{D}_2$$

To prevent high D_2/H_2 and O_2 concentrations from forming, and igniting, within containment, a hydrogen ignition system is used.

The principle behind its use is to deliberately ignite the D_2/H_2 and O_2 mixture in low concentrations in a steam environment. The ignition of D_2/H_2 at low concentrations prevents severe pressure/temperature transients that could cause damage to the containment envelope (which could occur if high concentrations of D_2/H_2 were allowed to build up to explosive level and ignite).

The hydrogen igniters are heating coils, similar to a heating coil on a stove, which will heat to $\geq$750°C to cause the ignition of the D_2/H_2. In the Bruce and Darlington units, these igniters are located at several different elevations within the reactor vault$^)$ and in the Pickering units they are in the fuelling machine vaults and service rooms.

4.3.13 Summary Of The Key Concepts

- Dousing occurs when increased pressure in the vacuum building main chamber forces water into the upper chamber, causing water to spill into the dousing headers.

- Following a large LOCA, for a NPC system, containment pressure quickly starts to rise. Box-up (or button-up) is initiated on one or more of the initiating parameters. All the PRVs (APRVs followed by main PRVs and IPRVs) will open to cope with the large pressure increase. Vacuum building main chamber pressure will increase. This will cause dousing to occur to reduce main chamber pressure. As containment pressure reduces, the large PRVs will close, followed by the IPRVs and APRVs. The IPRVs, and/or APRVs, depending on the station, will modulate to maintain pressure subatmospheric.

- Following a small LOCA, for a NPC system, containment pressure slowly starts to rise. Box-up or button-up is initiated on one or more of the initiating parameters. The vault coolers will act to condense the steam and will cool the vault atmosphere. This may limit the containment pressure increase to the point where no PRV action is required. If containment pressure continues to rise, the APRVs or IPRVs will open to reduce containment pressure.

- Once containment pressure is reduced, the APRVs will close, but will modulate to keep containment pressure below atmospheric.

- Airlocks allow for the passage of personnel and equipment into/out of containment without opening containment to atmosphere.
- The filtered air discharge system (FADS) will allow the contaminated air in the containment or vacuum structure to be discharged to atmosphere (at a controlled rate) after it is filtered to remove contaminants. This can maintain containment pressure subatmospheric.
- The hydrogen ignition system will ignite low concentrations of D_2/H_2 formed during a LOCA, thus preventing severe containment damage.

4.3.14 Vault Atmosphere

Purge Driers

The purposes of the vapour recovery system are:

e. Collection and recovery of D_2O vapour present in containment as a result of normal HTS coolant leakage

f. Removal of airborne tritium within containment

g. Maintaining containment pressure slightly subatmospheric

Point c) is our concern here. After the vapour recovery stage in the vapour recovery system, air is either returned to containment or discharged to atmosphere through the purge driers and the station stacks where it is further filtered and monitored by the contaminated exhaust system. This airflow through the purge driers normally keeps containment pressure subatmospheric (i.e. removes the air that has leaked into containment).

For a PSC system and older stations, a similar purge system to that mentioned above maintains the containment D_2O areas at a slight negative pressure, relative to other accessible areas.

Availability

Containment and all its associated subsystems (vacuum building, dousing water inventory, etc.) must be available during all unit states except when the unit is in the guaranteed shutdown state to preserve the fourth barrier to radioactive releases to the environment.

The containment system is considered to be available if it is capable of limiting doses to the public to within legal limits.

To minimize the containment unavailability, the following measures have to be taken:

- The containment system shall not intentionally be removed from service unless HT system(s) are at or below 90°C and the reactor(s) are in a guaranteed shutdown state.
- At least one door of each airlock shall be kept closed at all times.
- The system has to be tested according to a testing schedule to demonstrate that it meets the unavailability targets.
- The necessary maintenance shall be performed in a timely manner.

Reliability

Containment (and all its associated subsystems), like the SDSs and ECIS, must be very reliable. High reliability is achieved by independence, redundancy and selection of high quality components, as discussed in previous sections.

4.3.15 Summary Of The Key Concepts

- NPC pressure is maintained subatmospheric by the purge driers.

- Containment must be available at all times while the unit(s) operate to ensure that releases are minimized in the event of a LOCA.

- The reactor(s) must be shut down and cooled if the containment system is made unavailable.

- The reactors will be operating for normal testing of containment system components. But, in some cases (e.g. leak tests) the unit(s) must be shut down for testing.

4.4 Assignment

4.4.1 Shutdown Systems

1. State two general situations shutdowns systems protect against.

2. State the operational requirement for the shutdown system.

3. Describe the three shutdown systems found in CANDU reactors. State the ones used in the most recent reactors.

4. State 4 systems that shutdown systems must be independent of.

5. Explain the reason why the shutdown systems must be independent explain how it is achieved.

6. Explain why shutdown systems are fail-safe.

7. Name three interlocks between the operation of the shutdown systems and other systems. Explain the purpose of each interlock.

8. Explain the difference between absolute and conditional trip parameters and give one example of each.

9. For each of the following abnormal occurrences state the reactor parameter(s) likely to trip the reactor and explain why this parameter is chosen.

    a. Small LOCA

    b. Large LOCA

    c. LORA

    d. Loss of boiler feed

10. Explain the concept of redundant trip parameters.

11. State two occasions when the reactor might be tripped manually.

4.4.2 ECI

12. State the purpose of the ECI system.

13. Define the term loss of coolant accident.

14. The shutdown systems will operate to trip the reactor on a LOCA. State the parameters that will trip the reactor on a large LOCA and a small LOCA.

15. State the primary parameter for initiating ECI.

16. State three typical conditioning parameters for ECI.

17. Explain the purpose of each of the three operational phases of ECI.

18. Explain two reasons why HT pumped circulation is maintained for as long as possible after a LOCA.

19. Explain 3 reasons for the use of crash cooldown during a LOCA.

20. Describe the functions of the following major components:
    a. ECI water storage tank
    b. Accumulator tank or injection pump(s),
    c. Injection valves,
    d. Recovery sump,
    e. Recovery pumps,
    f. Recovery heat exchangers,

21. Describe the sequence of operation of the following major components:
    a. ECI water storage tank,
    b. Accumulator tank or injection pump(s),
    c. Injection valves,
    d. Recovery sump,
    e. Recovery pumps,
    f. Recovery heat exchanges.

22. Describe the availability requirement for ECI of a unit is to hot and pressurized.

23. Define the following ECI operational states.

    a. poised
    b. blocked
    c. recallable

24. Explain the action that must be taken in ECI when a unit is depressurized.

25. State two circumstances that might occur requiring the manual initiation of ECI.

4.4.3 Containment

26. Name the two types of containment systems found in CANDU reactors.

27. Explain how long term energy input to containment is minimized.

28. Explain the function of an airlock.

29. Define the term bow up or button up in the context of containment system. State when this action occurs.

30. Describe the normal function of the vault coolers during normal operation and after a LOCA.

31. State three functions of the dousing water.

32. Using the diagram in Figure 4.6 explain how NPC will operate following a large LOCA.

33. Using the diagram in Figure 4.4 explain how PSC will operate following a large LOCA.

34. Using the diagram in Figure 4.6 explain how NPC will operate following a small LOCA.

35. Using the diagram in Figure 4.4 explain how PSC will operate following a small LOCA.

36. Explain the purpose of the filtered air discharge system.

37. Explain the purpose of the hydrogen igniters.

38. Describe the availability requirements for containment.

39. Explain how PSC and NPC are normally kept below atmospheric pressure.

5 Reactor Systems

5.1 Annulus Gas System

In this section we will review the construction and purpose of the annulus gas system. We will examine the reasons for the selection of CO_2 as the gas used in the system and of system operation. This section will examine two major parameters the pressure and the dew point of the gas. Finally some abnormal conditions will be explored.

5.1.1 System Purposes

To understand the function of the annulus gas system, we should first review the location of the annuli in the calandria. Figure 5.1 indicates the location of the annulus gas as a boundary between the moderator and heat transport system.

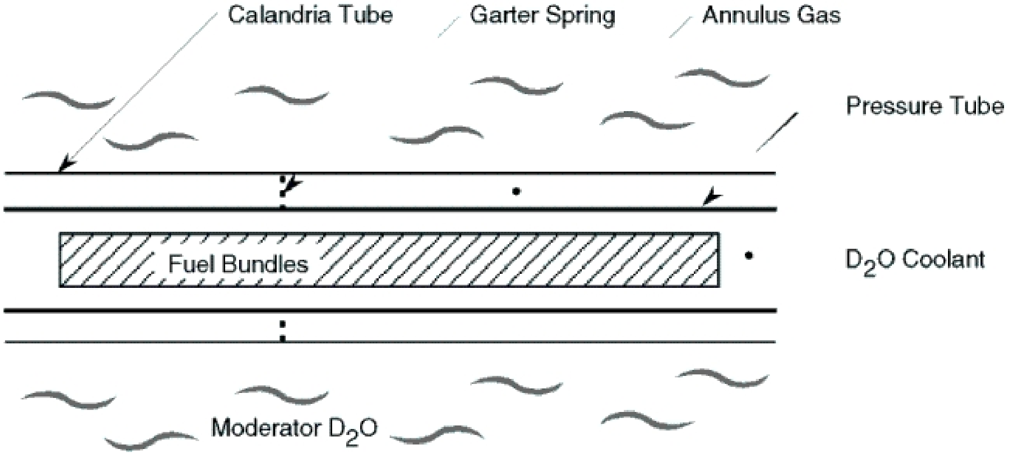


Figure 5.1 - Sketch of Annulus Gas Position

Serving as a separating medium, the two main purposes of the system include:

- To provide a method to detect and locate leakage from a pressure or calandria tube
- To provide thermal insulation between the hot pressure tubes and the relatively cool calandria tubes. This minimizes heat losses from the heat transport system coolant to the moderator coolant, thereby increasing the thermal efficiency of the unit
- Secondary purposes of the annulus gas system include:

- Providing a dry gas atmosphere in the fuel channel annuli to prevent corrosion of fuel channel components

- Providing a means to drain leakage from the heat transport, and moderator systems

5.1.2 Gas Selection

To fulfill the functions required of an annulus gas, the following properties are necessary:

- Low thermal conductivity (good thermal insulator)

- Low tendency to promote corrosion

- Low radiation fields (limited activation products)

Of the proposed annulus gases for CANDU stations, CO_2 has proven most suitable because of its good insulating properties. In the presence of water, carbonic acid (H_2CO_3) is formed. This acid is only mildly corrosive and is not a problem in the small amounts experienced. CO_2 can also form radioactive C^{14} from the neutron activation of C^{13}. Since C^{13} has a natural abundance of 1% and has a very small neutron absorption cross-section, the quantity of C^{14} produced is very small.

5.1.3 System Operation

Annulus gas flows through the fuel channel annuli, to an outlet header and then to the compressors. The compressors provide the motive force to circulate the annulus gas to the inlet header and back through the system. Circulation of the annulus gas is important for early leak detection since it ensures the dew point readings and gas sampling represents all of the annuli. Without circulation, it may take a long time (days) for a small D_2O leak to be detected. Because continuous circulation is so important, the system is designed to allow for gas flow through the channels even when the compressors are unavailable. This is achieved by supplying fresh gas from the bulk supply via the pressure regulating valve and venting to atmosphere via the purge line through contamination monitors. When a leak exists, most stations can also vent to containment for vapour recovery. This mode of circulation without the compressors is referred to as the continuous purge mode. The gas addition bottles through a pressure-regulating valve are the normal supply to the annulus gas system.

Dew point analysers in the main outlet header determine the system dew point. These readings as well as temperature and pressure are trended in the main control room for comparison purposes. There are also sample stations, usually in the main outlet headers, which allow for manual sampling of the gas.

The system piping is arranged such that any liquid in the system drains by gravity to the drain header. A moisture beetle in this header will indicate the presence of liquid. A beetle is a device that detects moisture from leaks. Beetles can detect leaks onto the floor and into pipes or tanks.)

Some stations have an oxygen addition system connected to the header downstream of the compressors. Small amounts of oxygen gas are added to the annulus gas to promote a harder oxide layer on the outside of the pressure tubes. Most stations will be retrofitted with this system for this reason. Oxygen can also be used to purge any solid C^{14} deposits by converting them to CO_2. This is used for decontamination purposes prior to outages (O_2 concentration used will be higher than normal operating values).

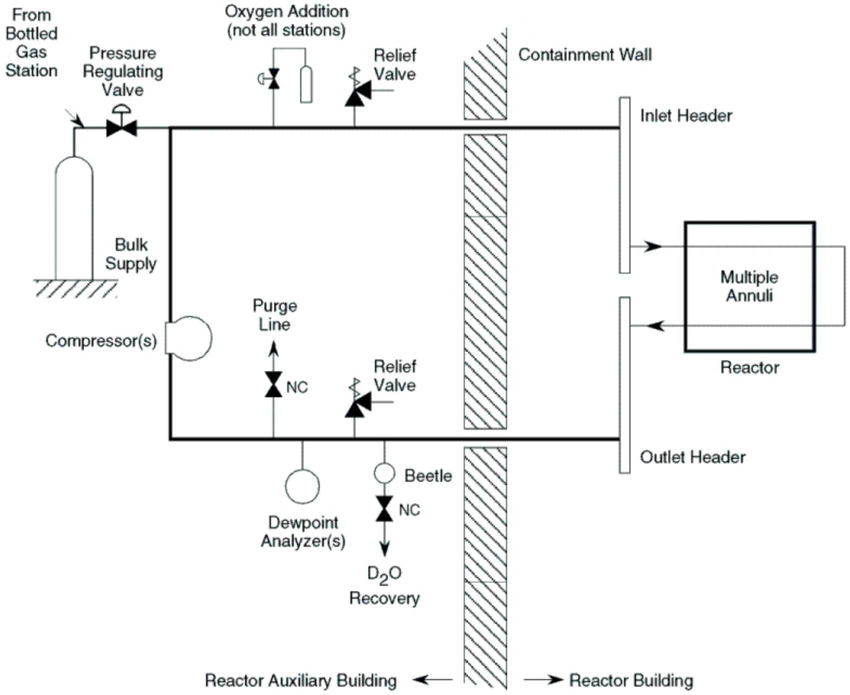


Figure 14.2
Simplified Annulus Gas System

5.1.4 Annulus Gas Pressure

The Annulus Gas System must be in service prior to unit start up or HTS pressurizing. Positive pressure is maintained to prevent the ingress of air. This system should remain pressurized even when the unit is shut down. As air ingresses, argon activation in air can lead to high gamma fields.

With the HT system cold, the annulus gas pressure is set to a low value, typically 14 kPa (g). As reactor power increases, the annulus gas pressure increases due to thermal expansion, typically in the range 25 to 100 kPa (g). When the pressure drops below set point, the operator can restore pressure via the pressure-regulating valve.

5.1.5 Dew Point

A dew point analyser(s) measures the moisture content of the annulus gas. The signals are sent to the control room where they are trended for comparison purposes so that a leak trend can be established. The rate of rise of dew point can also be established as a requirement for purging.

The allowable moisture levels in the annulus gas are usually expressed as a dew point and vary from station to station. A typical dew point operating range is -40°C to-10°C with -30°C as a normal operating value.

5.1.6 System Purging

Whenever the moisture content of the gas approaches the dew point upper limit, the gas should be purged. Fresh dry gas is used to replace the impure gas for the following reasons:

- To remove accumulated moisture that would otherwise contribute to high corrosion rates and mask small leaks. The reasons for purging include preventing build-up of corrosion products and preventing blockage of the interconnecting tubing for the channel annuli.

- To remove corrosive impurities, the most critical being nitric acid formed from N_2 and O_2 via air ingress.

- To remove air in the system, typically following maintenance to the system.

- To reduce gamma fields in accessible areas, when Ar^{41} has formed as a result of air ingress.

- To lower the dew point prior to startup of the reactor from a cold shutdown. As the reactor heats up, the temperature and pressure will increase in the annulus gas system. The partial pressure of any water vapour in the system will also increase, raising the dew point. To counter this effect, the dew point is lowered prior to heatup by a purge with dry gas.

- To maintain leak detection capability by maintaining gas flow through the system when the compressors are unavailable.

5.1.7 Summary Of The Key Concepts

- CO_2 has the beneficial properties of:
    - Low thermal conductivity
    - Low corrosion
    - Limited activation products
- Annulus gas must be circulated or purged to ensure dew point measurements and gas sampling are representative of all of the annuli.
- System pressure should be kept above atmospheric pressure to prevent air ingress. A typical range is 25 to 100 kPa (g).
- Dew point is monitored to detect moisture from leaks. A leak tight system should have a dew point range of -40°C to -10°C.
- Purging may be necessary to:
    - Remove accumulated moisture
    - Remove corrosive impurities such as nitric acid
    - Remove air from the system
    - Reduce gamma fields
    - Maintain leak detection capability when the compressors are unavailable
    - Lower the dew point before a cold startup

5.1.8 Abnormal Unit Conditions

High Annulus Gas Pressure

Annulus gas pressure can increase due to the following causes:

- Pressure tube rupture
- Thermal effects due to increases in reactor power
- Pressure regulating failure

Annulus gas overpressure can cause strain, fatigue or even rupture of the calandria tubes or secondly, fatigue or rupture to the bellows seals joining the annulus gas system to the pressure tube end fitting.

Pressure relief valves provide overpressure protection. Some stations use rupture discs on the compressor outlet in combination with the pressure relief valves.

Low Annulus Gas Pressure

Annulus gas pressure can decrease due to the following causes:

- System leakage
- Loss of bulk gas supply
- System shrinkage on reactor cooldown

It is possible to draw vacuum on the system if it is isolated and cooled. Pressure below atmospheric in the annulus gas system could cause the collapse of calandria tubes. Where possible, the system should be repressured via the bulk storage and any leaks repaired. Air in-leakage is also a concern at low annulus gas pressures because of the resulting increase in radioactivity.

Annulus Gas Leakage

Annulus gas can escape through piping leaks or channel bellows leaks. This can present a radiation hazard as well as reduce the ability to check pressure trends. The escaping annulus gas from any leakage points may contain radioactivity in the form of:

- C^{14}, an activation product, as CO_2 gas or as a particulate
- Entrained fission products and loose contamination from fission products
- Tritium from D_2O leakage

Annulus gas leakage can also result in low annulus gas pressure which, as mentioned above, may lead to air in-leakage.

Air in the Annulus Gas

Maintenance work or system leaks allow air ingress into the annulus gas.

The presence of air leads to radioactive hazards and the production of corrosive nitric acid (from N_2). The predominant radiation hazard is Ar^{41}, an activation product. Other radiation hazards include C^{14} produced from N^{14}, and N^{16} and O^{19} from O^{16} and O^{18}. Moisture from air in the system may mask leaks.

High or Increasing Moisture Content

An increase in dew point indicates an increase in moisture content of the annulus gas.

Possible causes of high or increasing dew point may be:

- Pressure tube leak
- Calandria tube leak
- Air in-leakage
- Impure annulus gas supply

For a persistently high dew point after purging, the most probable cause is a pressure tube leak, because of HT system high pressure and temperature. Two operational concerns exist with increasing dew point. Firstly, that a contaminated system is leaking with radiological concerns and the potential for a subsequent LOCA with possible fuel and calandria tube damage. The leak will eventually increase over time when power changes produce temperature changes in the leaking system. Secondly, a high temperature and pressure hazard exists in the case of a HT system leak.

5.1.9 Leak Location

To locate the leak source, a sample of condensed fluid is obtained by passing a stream of moist annulus gas through a cold finger. A cold finger is a trap in dry ice or cryobath that freezes the moisture. The sample is then analyzed to determine if the source is the HT system or the moderator. A stagnant mode of operation is then used to locate the leaking annulus. The compressors are shut down and isolated with the purge valves closed to:

- Maximize condensation of D_2O in defective channels

- Reduce the spread of moisture throughout the annulus gas system

A leak search also includes checks of channel outlet temperatures. The leaking fuel channel transfers heat from the pressure tube to the calandria tube via the leaking D_2O. If the gas space surrounding the leaking pressure tube fills with D_2O the heat transfer rate increases to effectively lower the channel outlet temperature. However, the channel outlet temperature data may not indicate the leaking pressure tube until sufficient fluid condenses and accumulates. It should be kept in mind that low channel outlet temperatures can also result from other reasons such as the pressure tube touching the calandria tube.

Note that a beetle alarm may take a long time to come in, depending upon the leak location and size. Sight glasses may also be available in some stations to detect liquid flow from individual annuli.

5.1.10 Summary Of The Key Concepts

- For the following conditions the operating concerns are given:

Conditions	Operating Concern(s)
High gas pressure	Failure or rupture of calandria tubes, failure or rupture of bellow seals if overpressure protection fails.
Low gas pressure	Air in-leakage, collapse of calandria tubes.
Gas leakage	Radiation hazard, reduced ability to check pressure trends.
Air in system	Radiation hazard primarily (Ar^{41}), production of corrosive nitric acid, moisture masking leaks.
High or increasing dew point	High pressure and temperature hazards with potential for a LOCA, radiological concerns.

The system may be made stagnant to determine the location of a confirmed leaking annulus by maximizing condensation of D_2O in the defective channels and reducing the spread of moisture throughout the annulus gas system.

5.2 Shield Cooling Systems

There are three types of shields used in CANDU reactors to protect personnel and equipment. These shields are as follows:

a) Calandria End Shields – protects personnel against γ in the reactor vault during unit shutdowns only.

b) Biological Shield – protects personnel against radiation, mainly γ and fast neutrons during unit operation.

c) Thermal Shield – protects equipment and structures against heat generated by the absorption of nuclear and thermal radiation emitted by the reactor.

In most stations the thermal and biological shields are combined.

This section covers the normal and shutdown cooling requirements of the shield cooling systems and the adverse consequences of the loss of system cooling. The draining of the end shield cooling system will also be discussed.

5.2.1 Calandria End Shields

Cooling Requirements

During normal operation, heat is generated in the end shield components by both radiation absorption (neutron plus γ) and by heat conduction. This heat cannot be allowed to build up, since it could result in reactor component damage due to excessive thermal stress. The end shield cooling system must remove this heat.

Upper and lower temperature operating limits are set for the end shield to prevent excessive thermal stresses from developing between the end shield and the calandria. The calandria shell and the end shield components are welded together and contain many rolled joints. An excessive ΔT in either direction will cause increasing differential expansion, which is severely constrained because of the design. Structural damage such as fractured welds, failed rolled joints, and displaced shielding slabs (where installed) may occur. A very important parameter then, is the temperature difference (ΔT) between the moderator and the end shields. (Typical values of end shield temperatures are ~60°C at the inlet and 65°C to 70°C at the outlet. Typical moderator inlet/outlet temperatures are 40°C/60°C).

At full power, the heat produced in the end shields will typically be less than 1% of total reactor thermal power. The heat sources are divided as follows:

a) About 30% of the heat is due to absorption of neutrons and γ from fission and fission products (decay γ).

b) The rest is due to heat conducted from the hot end fittings and the moderator.

Design Types

All CANDU reactor end shields are water cooled and are of two basic design types.

The first design uses carbon steel slabs, cooled with light water (Fig. 5.3). The carbon steel slabs are keyed together to make up a single thick section centered in the end shield. This thick section, combined with the channel shield plugs, provides the shutdown shielding for the end of the reactor. Cooling is provided between this steel shield and each of the tubesheets. Cooling flow is directed from the bottom to the top of each shield and through the space provided by the lattice tubes (for end fittings of the fuel channels).

The second design uses carbon steel balls for the shielding media, and is also cooled with light water (Fig 5.3). This design features better heat transfer for improved cooling and a lower construction cost than the slab design. This design is also more tolerant of high ΔTs, in terms of thermal stressing of the end shield and calandria components. All of the newer stations use this design.

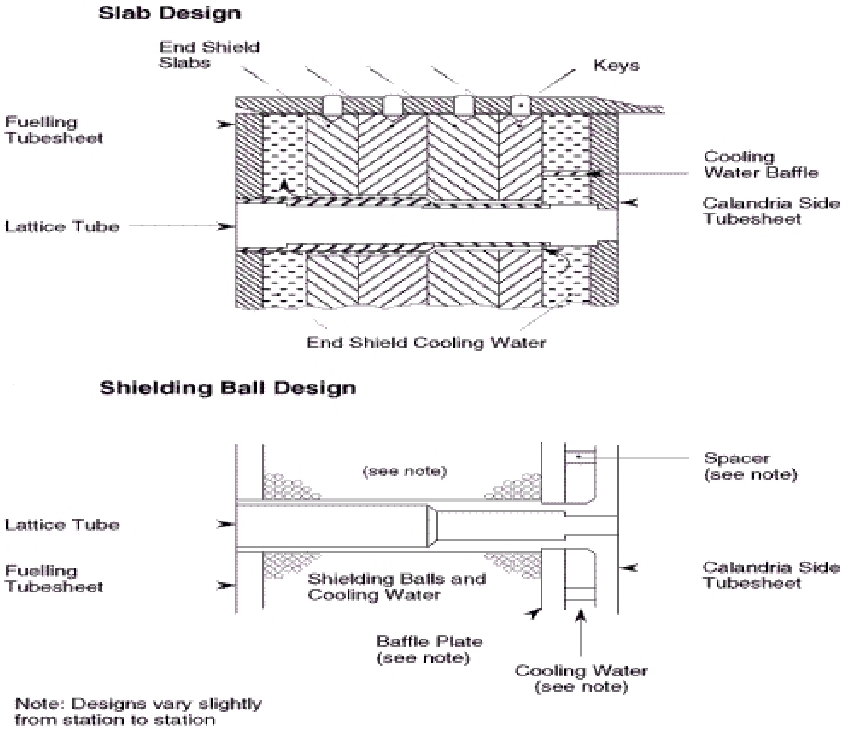


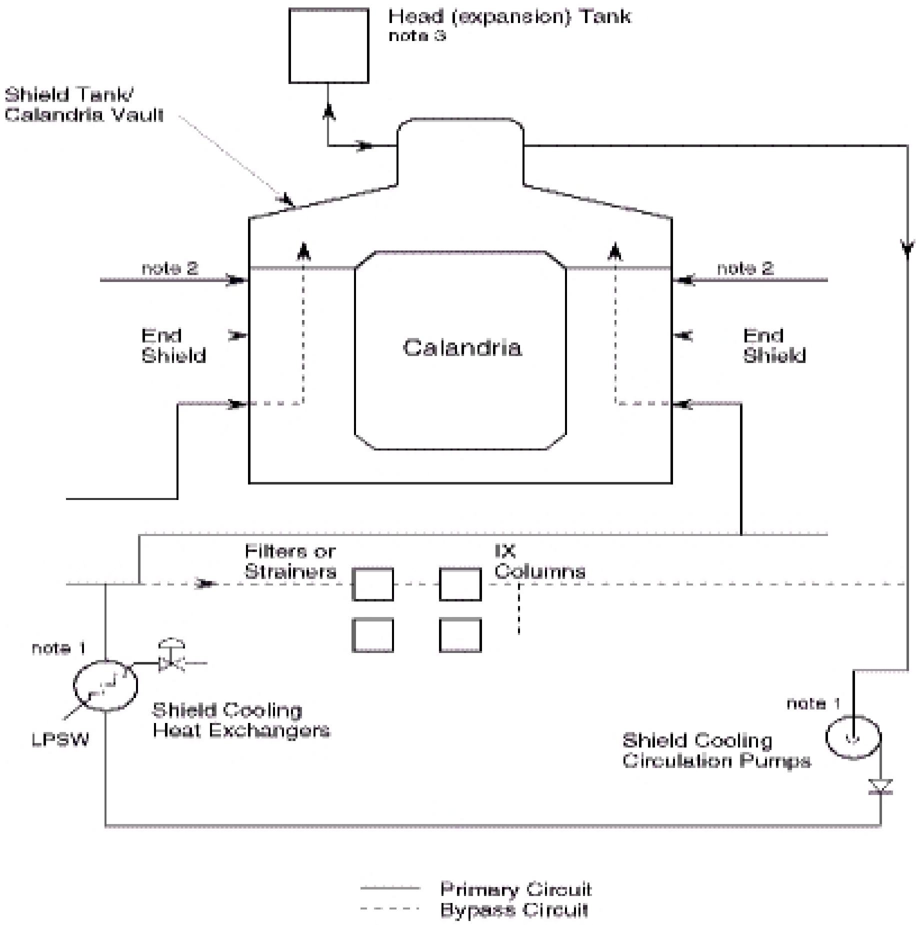
Figure 5.3 - Basic End Shield Designs

5.2.2 End Shield Cooling

A typical shield cooling design is shown in Fig. 5.4. The shield cooling system consists of pumps, heat exchangers, a bypass purification circuit and a head (expansion) tank.

The system recirculates demineralized light water through the end shields to pick up the heat from the shielding slabs or balls. The water is cooled, cleaned and used for shielding elsewhere in the system (ie. in the shield tank, if installed).

The circulated water is purified by filters (or strainers) and IX columns to minimize and remove corrosion products. These corrosion products occur because carbon steel is used in the end shields (steel balls or slabs, shield tank). These products must be removed to minimize contamination spread by the transport of activated corrosion products. To minimize corrosion, the pH of the shield cooling system is controlled to between 9.8 and 10.7 by the use of LiOH resin in the IX columns.



Note :
1. Number and capacity of components varies from station to station.
2. To baffle area or distribution pipes in tank.
3. Connected directly to pump suction in some stations.

Figure 5.4 - Simplified Flow Diagram for End Shield/ Shield Tank Cooling Systems

The head (expansion) tank is connected to the shield tank extension at the top of the reactivity mechanism deck, or directly to the pump suction in some stations. Its function is to accommodate shrinkage and swell of the coolant thus ensuring proper level is maintained, and to provide a positive suction head to the circulating pumps to prevent cavitation. Gamma and neutron fluxes can cause radiolysis to occur in the end shields, causing a hydrogen hazard in the head tank. To minimize this hazard, the head tank is open to contaminated exhaust to vent off the hydrogen, and in some stations may also be purged with nitrogen.

The pumps circulate the coolant through the end shield (and shield tank), the heat exchangers and the purification loop. The pumps are supplied by Class III power to ensure circulation is restored rapidly following a loss of Class IV power. This is because of the potential damage due to thermal overstressing of the end shield/calandria (due to loss of cooling flow).

The heat exchangers transfer heat from the coolant circulated through the end shield to service water. Temperature control is achieved by regulation of the control valves on the service water side of the heat exchangers. The temperature is controlled at approximately moderator temperature, hence avoiding large ΔT's and the resultant thermal stresses between the end shield and calandria. This service water then transfers heat to the environment.

Parameters, other than end shield and heat exchanger inlet/outlet temperatures, available for monitoring cooling are:

- Shield tank/head tank levels, to ensure that adequate coolant is available for cooling ie, no dry spots exist, and to ensure the circulating pumps do not cavitate. These levels will also indicate temperature changes by indicating shrinkage and swell of the coolant. As well, this may mean there are leaks from the system.

- Gross flow of the coolant, ensures coolant is flowing and will also automatically initiate additional pumping capacity as required.

- Pressure measurement at the pump's suction, discharge, HX discharge and ΔP across the HX will indicate flow problems, ie, break locations, flow blockages, etc.

5.2.3 Loss of End Shield Cooling

The temperature of the end shields will immediately increase if there is a loss of cooling. This could cause a large ΔT between the end shield and calandria. Prompt actions are required which would include the following (typically, only a few minutes are available before the second step in the following list would be required):

1. Check for, and correct cooling system deficiencies. Possible causes are:
    - Service water and temperature control valves operation
    - Pump operation (pumps cavitating and coolant not circulating, etc.)
    - Shield tank and head tank level low
    - Large leaks (low pressures, low head tank level)
    - Moderator cooling system malfunctioning, causing increased heat transfer to the end shields
2. If the above checks/actions are unsuccessful, reactor power must be reduced until heat removal capability of the shield cooling system matches heat production. In some stations, this occurs automatically via a reactor setback on loss of ESC flow or pump shutdown.
3. If the above actions are not successful, a cooldown of the HTS (or crash cooldown in some stations) will be required.

5.2.4 End Shield Cooling System Requirements

The end shield cooling system must be functional at all power levels of reactor operation. It can only be removed from service if certain conditions are met. Although the details are different from station to station in general, the shield cooling system may be shut down if the following conditions are met:

- The reactor has been shut down for a specified time period (4 to 24 hrs)
- The main moderator temperature is less than a specified limit (~38 to 40°C)

- The HTS is cold ($\leq$ ~55°C)

These conditions ensure that the heat input into the end shield will not result in damage due to overstressing. With the reactor shutdown, and the HTS and moderator cooled, the heat source is mainly decay γ, which will be at extremely low levels, as compared to operating heat sources. This heat will be taken away by natural convection by the reactor vault atmosphere, moderator and HTS systems (all still being cooled).

Special precautions must be taken if the end shield is to be drained. Without water in the end shields, the natural convective cooling of the water within the end shield (mentioned above) would be lost, resulting in possible thermal stresses and damage. Without the shielding effect of the water, radiation fields may reach thousands of R/Hr at the reactor face. The corrosion protection provided by the water will also be lost, resulting in corrosion (due to air access to wetted surfaces) and eventual activation and activity transport. Draining of the system would require:

1. Detailed stress analysis to ensure stresses due to thermal effects do not exceed design limits
2. Measures to control corrosion are implemented
3. Access to reactor areas is restricted or additional shielding is provided to compensate for the loss of shielding from the water

Note that CNSC approval may also be required (depending on the station), as increased exposure risks to station personnel will exist. As a result, the shield tank and end shield cooling system will not be drained under normal circumstances.

5.2.5 Thermal Shield

The thermal shields used in CANDU reactors are also of two basic designs.

The first design uses shield plates internal to the calandria. Thick stainless steel liner plates are supported inside the calandria shell. Gamma radiation, fast neutrons (due to leakage) and thermal heat from the core result in heating of these plates.

Cooling of the thermal shield is performed by moderator D_2O through the moderator cooling circuit. Unfortunately, in this design, sufficient heat escapes the reactor to make it necessary for a cooling system in the surrounding concrete shielding. This will be discussed next, when considering prevention of damage to the biological shield. This system does reduce the required capacity for the biological shield cooling system.

The second approach uses a water filled shield tank that surrounds the calandria. Some stations use a steel tank, others use a steel lined concrete structure. This tank encloses and supports the reactor core and the water in it absorbs the γ, fast neutrons and heat from the reactor core. This water shield provides biological shielding at the top of the reactor (called the reactivity mechanism deck) and provides shutdown access shielding elsewhere. This design is used in the newer stations. Because no separate biological shield cooling is necessary, the advantages of this design are reduced construction costs and time compared to the previous design (which requires extensive runs of cooling pipes embedded in the biological shield). The cooling of this thermal shield is via the end shield cooling system as previously shown in Figure 5.4.

In both cases of thermal shield design, the cooling of the thermal shield is performed as a function of another system, ie, moderator or shield cooling system. Thus the percentage of heat removed in these cooling systems also includes the heat generated in the thermal shields.

5.2.6 Biological Shields

The design of the biological shields reflects the effectiveness of the thermal shield.

For the thermal shield internal to the calandria, additional shielding surrounding the calandria is required. This shield, known as the biological shield, is made of heavy concrete and is comprised of the calandria vault walls, roof, floor, and hatches. This shield is heated due to the absorption of neutron and γ radiation from the core as well as thermal heat convected and radiated from the core. Cooling of this shield is required to limit the concrete temperature to ~60°C. At higher temperatures, water is driven out of the concrete, resulting in the following adverse consequences:

a) Thermal stresses may cause spalling and cracking in the concrete, hence its physical strength will be reduced.

b) With less water in the concrete, it is less effective as a neutron shield.

Cooling of the concrete of the biological shield is provided by water flow through pipes embedded within the concrete. The cooling water is circulated by an independent system, similar to the end shield cooling system, consisting of pumps, heat exchangers, head tank and a bypass filter system. The typical heat removed by this system is < 0.1% of reactor full power.

For the water filled shield tank or vault design of thermal shield, cooling of the surrounding concrete biological shielding structures is not required. The effectiveness of the thermal shield is sufficient to eliminate the need for embedded cooling pipes in the containment/shielding structures.

5.2.7 Summary Of The Key Concepts

- The end shield and biological/thermal shields require cooling to remove heat derived from the absorption of γ radiation, neutrons and thermal heat from the reactor core. Cooling is required while operating at any reactor power level, and for some time after shutdown.

- The end shield temperatures must be limited to prevent thermal stresses from occurring between the end shield and the calandria shell. Damage could result from high stresses.

- The heat removal from the end shield at power will be 0.2 to 0.6% reactor full power. When shut down with the HTS and moderator cooled, heat production will be mainly due to decay γ. This will be a small heat source and convective cooling will be adequate.

- Heat removal from the end shield occurs via heat transfer from the steel slabs or balls to the circulated coolant, then in the heat exchangers from the coolant to the service water, which is rejected to the environment.

- Special precautions must be taken if the end shield is to be drained. Stresses resulting from the loss of cooling must be determined; measures to protect against system corrosion and increased radiation fields must be taken.

- The end shield cooling system purification loop is required to remove activated corrosion products from the system. These corrosion products are removed to ensure that activity transport in this system is minimized.

- Other parameters that are monitored to ensure adequate end shield cooling are system flow, shield/head tank levels, and system pressures.

- The required actions on the loss of end shield cooling are to restore cooling, reduce reactor power and a cool down of the HTS as required to maintain ΔT's.

- Loss of cooling to the thermal/biological shields will result in overheating of concrete structures, which will result in the concrete drying out, leading to damage and reduced shielding against neutrons.

- The heat removal from the biological shield (where cooling systems are installed) will be <0.1% reactor full power.

5.3 Assignment

5.3.1 Annulus gas

1. State three desirable properties of CO_2 as an annulus gas:
2. The annulus gas system is normally circulating even when the unit is shut down. Why is this desirable?
3. Dew point is one of the most important operating parameters for the annulus gas system. Why is this the case?
4. Why is annulus gas pressure monitored?
5. State typical operating ranges for the following parameters:
    a. Dew point
    b. Pressure
6. State six reasons why purging would be required.
7. Under what operating condition would the annulus gas compressors be shut down and isolated?
8. For given abnormal conditions, state the indicated number of major operating concerns:

a) High annulus gas pressure (2)

b) Low annulus gas pressure (2)

c) Leakage of the annulus gas (2)

d) Air in the annulus gas (2)

e) High or increasing moisture levels (2)

5.3.2 Shield cooling

9. Name 2 sources that heat the shield and state the approximate reactor thermal power that is dissipated in the end shield. .
10. Describe the consequences of not cooling the end shield.
11. Describe the heat transfer path for the end shield cooling system.

12. Explain why the end shield cooling requires a purification system.

13. Name three parameters, in addition to temperature, that are monitored to determine the performance of the shield cooling system. Explain the importance of each.

14. State the three major actions that need to be taken when end shield cooling is lost.

15. Explain the three conditions that must be satisfies before the end shield cooling system can be taken out of service.

16. Besides the approval of the regulator state three precautions that will be required before the end shield is drained.

17. State the heat source for the biological and thermal shield. Explain the adverse consequences fof failing to remove this heat.

18. State the approximate reactor thermal power delivered to the thermal shield.

6 Fuel

6.1 Fuel Performance

The performance of CANDU fuel is assessed in four main areas:

a) Maximized power production per bundle and per channel

- Maximized power production over a period of time (burnup)

b) Minimum number of failures

c) Performance under major upset conditions

Fuel design and method of operation of particular unit largely determine (a), (b) and (d). It can be stated that the first two conditions will generally be achieved making fuel failure our critical factor.

It must also be remembered that the fuel operates in a hostile environment. The HTS operates at high pressures, a temperature of about 300°C and at a pH of about 11 in high radiation fields. Fuel bundles can spend up to eighteen months in the reactor.

In practice, operation of CANDU reactors over the years has not highlighted fuel failures as a significant problem. The introduction of CANLUB fuel and changes in operating strategies have reduced fuel failures to less than 0.1%. It should be noted that only one element usually is found to be defective in a bundle. Thus the defect statistics based on defective elements for CANLUB fuel drops to 0.002%. This low figure does not mean that the problem is solved. Efforts must continue to at least maintain and, if possible, improve these figures.

It must also be recalled that the fuel provides the first two barriers to the release of fission products (i.e. the ceramic fuel itself and the fuel sheath). Fuel failure inevitably results in the release of fission products into the heat transport system.

This section will discuss potential causes for fuel failures; mechanisms to prevent fuel failure(s) and methods to detect and remove failed fuel from the reactor during normal operation. This section will also discuss methods available to the operator to ensure fuel bundle power limits are not exceeded and how the fuel is protected against dryout and centerline melting.

6.1.1 Units of Burnup

Burnup Units

Three different units are in common use for describing the state of the fuel. Each is described below.

Equivalent Full Power Days (EFPD)

Perhaps the simplest way to specify the burnup of a given fuel bundle is by the number of equivalent full-power days (EFPD) it has resided in the core. This is the number of days of exposure to full power flux. (A bundle exposed to 50% of full power flux for two days would have a burnup of one EFPD). Documents for non-specialists, such as public relations publications and management memos, often use this measurement.

Energy Extracted per Unit Mass (MWh/kgU)

Each watt of power production requires about 3.1×10^{10} fissions per second (see Section 1.1). One megawatt-day of heat energy production requires the neutrons to fission about one gram of fissile material. One way to specify burnup, then, is in terms of the total cumulative heat energy extracted from the fuel. The unit is megawatt-hours per kilogram uranium (MWh/kgU). Accountants or people involved in fuel purchasing are most likely to use this measurement. Note that the MWh here are thermal, not electrical, energy.

Total Neutron Exposure (n/kb)

The rate of fuel burnup is proportional to the neutron flux. The accumulated burnup over a specific period of time (t) is therefore proportional to the product of flux and time (ϕt). This product is known as the total neutron exposure of the fuel; it is the fuel burnup measurement of choice for reactor physicists, the fuelling engineer, and other specialists. The units of neutron exposure are:

$$\phi t \rightarrow \frac{\text{neutrons}}{\text{cm}^2\text{s}} \times \text{s} = \text{neutrons}/\text{cm}^2$$

The total neutron exposures in these units are very big numbers, so a common modification of the unit neutron/cm^2 is the neutron per kilobarn, defined by changing the unit of area to the kilobarn:

$$1\ \text{kb} = 10^3\ \text{b} = 10^3 \times 10^{-24}\ \text{cm}^2 = 10^{-21}\ \text{cm}^2$$

The relation between n/kb and n/cm^2 is then:

$$1\ \text{n}/\text{kb} = \frac{1\,\text{neutron}}{10^{-21}\,\text{cm}^2} = 10^{21}\ \text{neutrons}/\text{cm}^2$$

The typical average exit burnup for fuel bundles discharged from a CANDU reactor is around 1.8 n/kb. Individual bundles in the core at any given moment have exposures that range from 0 to 2 n/kb or so.

One way to look at this rather arcane unit of exposure is to say that 1 n/kb is equivalent to 10^{21} n-cm per cm^3, that is, the flux exposure measures the accumulated track length of all neutrons that have passed through a unit volume of the fuel during its time in the core.
The approximate relationship among the burnup units is:
100 MWh/kgU $\approx$1 n/kb $=10^{21}$ n/cm^2 $\approx$ 115 EFPD

The units for energy extracted is not exactly proportional to the unit for neutron exposure, as the energy extracted by a given flux exposure is slightly different for fresh fuel and highly irradiated fuel. The conversion between EFPD and the other burnup units above assumes a CANDU reactor with a full-power average flux of 10^{14} n $\text{cm}^{-2}\text{s}^{-1}$.

6.1.2 Failure Mechanisms

The seven main observed failure mechanisms for CANDU fuel during reactor operation are:

1) Manufacturing faults - particularly in terms of metal and welding quality

2) Fretting and erosion due to debris in the HTS (particularly for the initial core load)

3) Cracking due to hydride cracking around the endcap welds, or stress corrosion cracking of the Zircaloy sheathing

4) Careless handling of fuel, leading to mechanical stresses on the sheath (i.e. due to chipped ceramic, etc.)

5) Fuel overrating, i.e. producing too much power from a bundle

6) Ramp failures or bundle overpowering, i.e. large, rapid changes in reactor power from one steady state condition to another. This is especially important for bundles that have been in the core for a long time

7) Loss of cooling of a bundle

Methods that can be used to minimize the fuel failure mechanisms listed above are:

1) Careful inspection of all fuel bundles before loading into the reactor to eliminate those that have obvious flaws

2) Good housekeeping to ensure that debris is not introduced into the HTS

3) Ensure that all HTS chemical parameters are strictly enforced

4) Careful handling of all fuel bundles, which includes manual handling of new bundles and handling of new and spent fuel by the fuelling machines

5) Proper fuel and physics calculations and proper fuelling operation will prevent placing too many new bundles in high flux zones of the core, etc.

6) Minimize large, rapid changes in reactor power from one steady state condition to another

7) Both flow and temperature in the channel are monitored during fuelling since this is the most likely time a flow blockage will occur (causing a loss of bundle cooling). Under normal operation, flow measurement is limited to fully instrumented channels only. All channel outlet temperatures are monitored but, if a channel is boiling, outlet temperature alone will give no indication of flow blockage.

These procedures will do much to ensure that fuel failures are minimized.

The potential failure mechanisms dealing with loss of cooling and bundle overrating are discussed below.

6.1.3 Flux Shape

The flux in a CANDU reactor is flattened to maximize the power output of the core. Several different techniques are employed to get average flux in the core as close as possible to the maximum flux in the core.

- Use of a reflector

- Adjuster rods
- Bi-directional fuelling
- Differential burnup
- Liquid Zones.

These methods, properly applied, improve the general flux shape of the core. However, if one looks closely at the detail of the flux there are many little bumps and valleys.

6.1.4 Flux Shape Details

The actual flux shape in the reactor core differs somewhat from the overall smooth flux shape just described. Neutron absorption in fuel and in reactivity devices distorts the smooth flux shape. For an equilibrium fuelled CANDU, the overall flux shape is nearly constant during operation, but there are local bumps and hollows that change strength and location because of changes in xenon concentration, because of fuel burnup and on-power fuelling, and because of changes in the configuration of the reactivity devices.

Local flux peaks must be controlled so that safe operating limits on fuel bundle power and channel power are not exceeded. Peaks can affect fuel power directly or by distorting measurements of power. In routine operation, a good fuelling strategy coupled with effective power regulation limits the peaks.

Anything that could produce an unanticipated local peak, such as a stuck rod, or an uncontrolled xenon oscillation requires attention.

6.1.5 Flux Depression around Absorbers

Figure 6.1 shows the thermal neutron flux depression across a CANDU fuel bundle. Notice that the reduced flux extends beyond the boundary of the bundle. The thermal flux just outside the bundle results from the random motions of neutrons moving into the region from all directions.

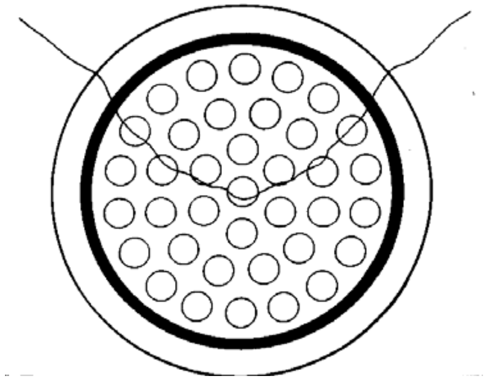


Figure 6.1
Depression of the Thermal Flux in a Fuel Bundle

The presence of a nearby absorber reduces the source of neutrons from that particular direction, so the flux is reduced. This effect is seen for any absorbing material in the core. Not only is the flux reduced in the region where neutrons are absorbed, it is reduced in the surrounding region as well. The flux depression gets less the further you are from the absorber.

6.1.6 Local Power Peaks and CPPF

The liquid zone control system, designed and operated to regulate bulk power, and to adjust zone average power, cannot effectively eliminate a local hot spot that might develop during operation. Such detailed flux shaping is accomplished routinely by selecting appropriate channels for on-power fuelling.

To describe the local peaks and valleys in the flux distribution we compare the actual flux distribution with an idealized reference flux shape. The reference flux shape derives from the shape that would exist if day-to-day variations could be averaged out. (This is variously called the time-averaged flux shape or the continuous fuelling model flux shape.) There is no possibility of achieving this theoretical shape, as burnup and fuelling in normal operation produce local fluctuations about the average. The fuelling engineer consults a channel power map based on the reference shape as an ideal target for fuelling.

Deviations in flux from the reference shape are called fuelling ripple. Fuelling ripple, defined for each channel, is the ratio of the actual (measured) channel power to the reference channel power. The off-line fuelling code generates a map of reactor fuel channels with ripple values for each.

For example, if a particular channel has a reference power of 6.5 MW (meaning that over many years of routine, full power operation the analysts expect power from this channel will average 6.5 MW), and the actual power is 6.2 MW before refuelling, the ripple is 6.2/6.5 = 0.95 for that channel. If the channel power reaches a steady 6.9 MW after refuelling, the ripple is then 6.9/6.5 = 1.06. Fuelling ripple changes continually with core conditions.

Given the fuelling ripple for every channel in the core, there will be one highest value of the ripple. This value is the channel power peaking factor (CPPF). Stations may discount high ripple in the outer one or two rows of channels at the edge of the core when selecting the CPPF channel. Stations may increase the measured CPPF to include uncertainties in measurement and analysis.

All channels and bundles in the core operate below their safe operating limit:

- if bulk power is controlled,
- if the overall flux shape is kept adequately flat, and
- if fuelling keeps local peaks acceptably low.

The regulating system accomplishes the first two of these, provided the operating staff ensures that zone levels operate within their normal operating range, and there are no flux distortions from unusual reactivity device configurations. The safety shutdown systems back up normal regulation. A later section discusses the Regional Overpower Protection System (ROP) - sometimes called the Neutron Overpower Protection System (NOP).

The third item in the list depends on selecting and fuelling the right channels. (Fuelling also affects the second item on the list). Now we will describe how the fuelling engineer selects channels for fuelling.

6.1.7 Fuel Overheating

Centerline melting of the fuel will cause pellet expansion, leading to stressing and failure of the fuel sheath. The fuel element centerline temperature, our principal concern, is dependent upon two factors:

1) The amount of heat produced in the fuel

2) The ability to remove heat from the fuel

The above can result in excessively large differential temperatures being required (between the fuel elements and the coolant), in order to transfer the heat being generated. This can lead to overheating of the fuel and/or fuel sheath.

Recall that our fuel material, UO_2, has very low thermal conductivity and that even under normal operating conditions with the fuel sheath temperature at less than 300°C the centerline temperature of high power bundles will approach 2000°C. The approximate melting temperature of UO_2 is ~2800°C. Our normal operating practices must ensure that fuel temperatures that could cause fuel failures are avoided.

The quality of heat removal can be verified by:

1) Flow measurement - fully instrumented channels (FINCH) and adequate number of HTS pumps in service (also ΔP monitoring during fuelling)

2) Temperature measurements where temperatures are useful (i.e.: at channel inlet at all times and at channel outlets when the channel is non-boiling (low power))

3) Pressure measurements in the HTS

4) Thermal power measurements, either by the fully instrumented channels (FINCHs) or secondary side measurements. Reactor thermal power can be calculated by using FINCH flows and temperatures (as representative of the core). By using various flows and temperatures on the secondary side, reactor thermal power can be calculated.

In a forced convection mode, as the coolant changes from subcooled to full film boiling conditions, heat transfer conditions will change considerably.

Consider a channel as reactor power (hence fuel temperature) increases. There will be an initial increase in heat transfer as initial (nucleate) boiling begins. As boiling becomes more pronounced, progressive steam blanketing (film boiling or dryout) will occur and heat transfer reduces. This reduction begins when Critical Heat Flux (CHF) conditions are exceeded (even slightly). The maximum heat flux that can be removed by nucleate boiling is termed the critical heat flux (CHF). The power in a channel at which critical heat flux conditions are met is termed the Critical Channel Power (CCP). Note that CHF conditions can be established even below the previously defined CCP (for a normal flux shape) if the flux shape deviates from normal. Changes in thermohydraulic conditions and/or flux shape will result in a new critical channel power for that channel.

We operate reactors such that the critical heat flux will not be reached under normal operating conditions. If full steam blanketing (film boiling) occurs, heat transfer will be mostly by conduction and radiation across the film and fuel temperatures will increase drastically (by 100's of degrees). Fuel failure becomes highly probable. Channel voiding increases reactivity and would further add to the problem.

Overrating will almost certainly produce excessive element centre line temperatures. This would eventually lead to centre line melting and pellet expansion, with a high probability of sheath failure. Gross overrating could cause pressure tube damage due to fuel bundle disassembly (deformation).

As mentioned previously, a combination of power produced and coolant conditions can cause fuel overheating.

With a standard full-power neutron flux profile, but with a reduced coolant mass flow through the channel, boiling will occur closer to the inlet (for a channel that is already in boiling). The bundles at the exit end of the channel will likely be subjected to dry out conditions and overheating of the final bundles is possible. However, that the bundles subject to overheating were not those subjected to the maximum neutron flux conditions.

A similar result would have been achieved by increasing the neutron flux levels with the coolant flow unchanged (overheating following overrating).

Similar effects can be shown using a non-standard or skewed flux profile. For this example, assume that the flux profile is skewed toward the channel outlet, i.e. the high flux, hence higher power production, occurs at the channel outlet. As the coolant flows through the channel, it gets hotter as it picks up heat from the fuel bundles, and the margin to boiling decreases. As this coolant (with a low margin to boiling) passes over the high power bundles at the channel outlet, film boiling will occur due to high bundle temperatures (these bundles will be much hotter than a normal bundle due to the flux shape). This will lead to fuel bundle overheating, with a higher probability of fuel failures.

Since flow in adjacent channels is in opposite direction, the skewed flux shape described above would produce a higher flux at the inlet end of these channels. Note that assuming all other channel conditions are similar to the channel mentioned in the paragraph above, the same amount of heat is being produced in these two channels. But, in this second case, the coolant is passing over the high power (hot) bundles with a much larger margin to boiling, since they are at the channel inlet. These bundles will be cooled without any boiling occurring. The bundles at the channel outlet, being cooler (these bundles will be cooler than a normal bundle due to the depressed flux at the channel outlet), will be adequately cooled without dryout occurring in the channel.

6.1.8 Power Limits

Fuel centerline temperatures must be limited, but it is not a parameter that we can measure in our reactors. This is further complicated by the fact that neutron flux in the reactor will vary axially and radially. Even within the fuel bundle itself, there is a variation in the thermal neutron flux (shown in Fig. 6.2). This flux depression is caused by the outer fuel elements absorbing thermal neutrons from the surrounding moderator. Thus, progressively fewer neutrons are available for the intermediate and inner fuel elements.

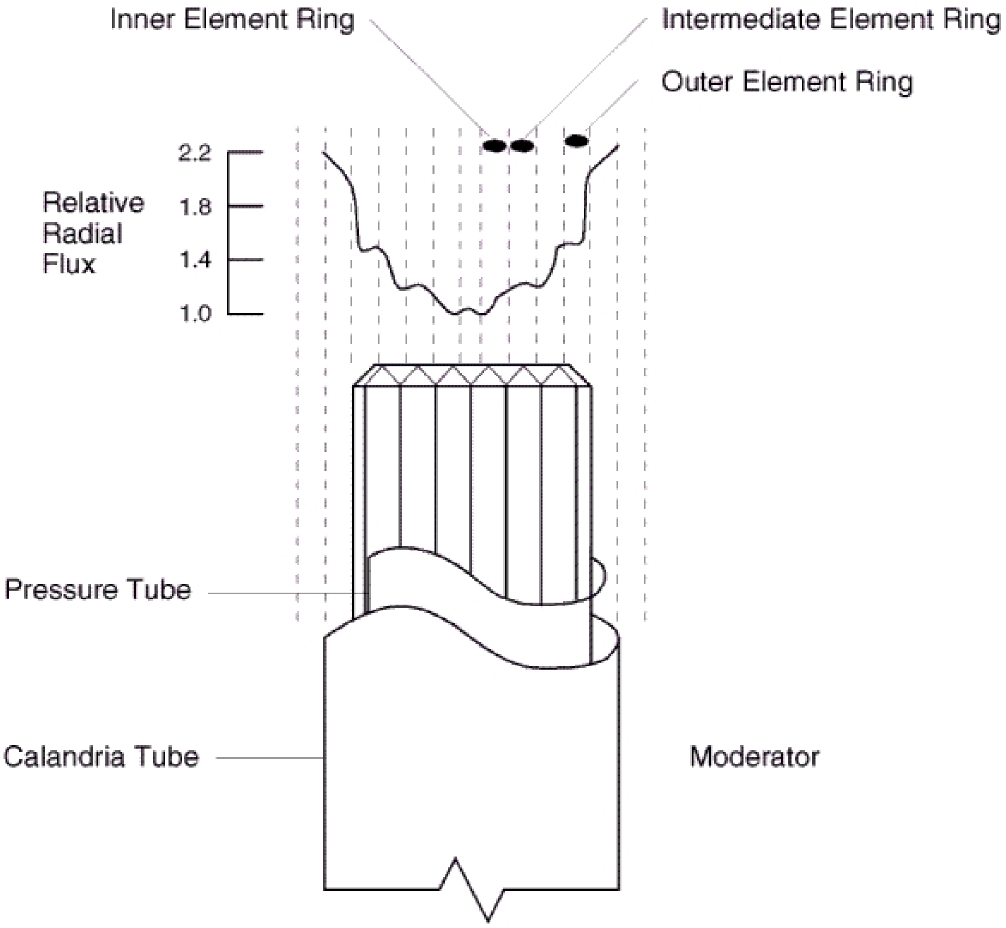


Figure 6.2 - Thermal Neutron Flux Depression In a Fuel Bundle

Taking these facts into account, at the design stage, the upper limit at which fuel failure is still unlikely must be established. The maximum bundle power limit must be below the power required to cause fuel failures.

The Station Licence contains the limiting values for fuel bundle, fuel channel and reactor power and coolant flow. Operating procedures and policies must ensure that these figures are not normally exceeded so that fuel failures and subsequent release of fission products are limited.

In most stations, bundle and channel power limits are specified to ensure that bundles are not overrated under normal operating conditions or during transients.

Limiting the channel power alone is not sufficient to ensure that no fuel bundle is overrated. This is because flux can deviate from its normal shape.

For example, a bundle power during normal operating conditions may be limited by the channel power limit (i.e. taking channel power, number of bundles and a normal flux distribution into account, the bundle will be producing powers below the licence limit to ensure the channel power is not exceeded).

Now let’s say that a flux tilt develops due to a Xe transient. This may result in the majority of the power being at the inlet end of a channel. Now, it is possible that a particular bundle at the high power end of the channel has its limit exceeded while the power limit for the channel is not being exceeded.

One note to make here is that as the bundle burnup increases, the maximum power that it can be subjected to before failures occur reduces. This is caused by the increasing sheath embrittlement together with mechanical stresses, mainly due to the internal buildup of fission product gases. We operate our reactors so as not to subject high burn-up bundles to high power, hence reducing this type of fuel failure.

6.1.9 Dryout Protection

6.2 High Power Protection

We will consider high power protection under two main headings:

- Regional Overpower Protection (ROP)
- Licence limits on bundle and channel power

6.2.1 Power Rise Limited by NOP/ROP

The ROP systems (one for each shutdown system) provide primary or backup trip coverage for a variety of process failures that cause excessively high power. The system caters particularly to power increases that are too slow to produce a rate log trip.

Each ROP system includes three arrays of self-powered in-core detectors to provide three trip channels. For adequate protection, at least one detector in each channel should see any event that produces high bulk power or high local power. Specifically, the trip setpoints ensure that a reactor trip occurs before heat production causes either centerline melting or fuel dryout anywhere in the core.

Centerline melting occurs if the rate of heat production in a fuel element exceeds the capacity of the pellet to transfer heat to the fuel sheath and into the coolant, so that the fuel centerline temperature reaches the melting temperature for UO_2 (about 2750°C). Fuel dryout occurs when the fuel sheath temperature gets so high that excessive boiling of coolant at the fuel surface produces a vapour barrier that limits heat removal from the fuel element.

Dryout results in rapid fuel heating followed by centerline melting. Typically, centerline melting occurs if a bundle power is too high (because of high local flux), and dryout occurs if the channel power is too high (because of high total power output along the channel). Analysis demonstrates protection from both.

The system designers cannot know the initial power in each channel, as these vary from day-to-day because of fuel burnup and refuelling. The designer also does not know what configuration the reactor will be in when a specific event occurs that requires a trip. Finally, the designer must provide coverage for a wide range of initiating events. In the analysis, a trip occurs when any channel power, initially at the reference channel power reaches dryout power (or any bundle reaches centerline melting). Protection for a power rise in a real core (that is, in a reactor with fuelling ripple) occurs because the ROP detector signals are raised (up calibrated) to protect the channel with the highest ripple.

To explain how the trip setpoints are determined and how trip coverage is affected, three items are discussed.

- The design basis set of flux shapes
- Determining the required trips for the reference flux shape
- Taking account of fuelling ripple (CPPF)

6.2.2 The Design Basis Set of Flux Shapes

Trip coverage analysis considers a very large number of events from a variety of initial reactor configurations, at minimum several hundred scenarios. These are events like loss of bulk power control, producing a slow uniform increase in power across the core, or draining of a single zone, causing a bulk power increase with a high local peak superimposed, etc. These and many other upsets are combined with various initial distortions of the reference flux shape core conditions (for example, reference core at steady high power, reference core with a xenon transient in progress, reference core with a rod stuck in core, etc.) The ROP system must provide overpower protection for a large number of initial flux shapes that could arise due to normal or abnormal movement of reactivity devices, together with changes in xenon concentration. The design basis set of flux shapes is a comprehensive set of flux shapes representing all analyzed upsets.

6.2.3 Reference Core Trip Coverage

Each detector must have a trip setpoint such that at least one detector in each array trips before any fuel channel reaches dryout, or before onset of centerline melting, whichever comes first. Conceptually this is quite simple. A computer simulation begins with the reactor in the reference flux shape and simulates each of the analyzed upsets in turn. It allows each design-basis flux shape to increase until the highest channel power reaches the power level corresponding to onset of dryout (or the highest bundle power corresponds to the centerline melting temperature). The computer then notes the thermal flux level at all the in-core detector locations.

As the computer analyzes each of the design basis flux shapes it sorts through the detector readings and selects the least restrictive set of trip setpoints (that is, with maximum margin to trip) that provides the necessary trip coverage.

As more and more restrictive accidents are analyzed, trip setpoints for all detectors move downward, perhaps into the range of 117% to 119%. In the early stages of the design, adjustments to detector locations and their distribution over the arrays improve trip coverage while optimizing the operating margin (margin to trip). The analysts may even make small changes to the reference flux shape (making the reference flux shape slightly different from the time-averaged flux shape). At the end of the process, each ROP system has a set of trip setpoints that provides complete coverage for all incidents in the design basis set**,** provided the reactor fuelling has produced the reference flux shape.

6.2.4 Effect of Fuelling Ripple

The ROP/NOP trip setpoints protect the idealized reference core, as just described. In the real core, fuelling ripple may result in the vulnerable channel (for a particular upset) with a higher power than the reference. The detector expected to provide trip coverage could be reading below the reference value. As power increases uniformly, the vulnerable channel reaches dryout (or a bundle reaches centerline melting) before the detector reaches its trip setpoint. The worst-case situation would be if the vulnerable channel was the CPPF channel (the CPPF channel has the highest ripple in the core). This difficulty is solved by recognizing that the actual detector readings don't matter, only the margin to trip matters. The safety system ROP detectors do not need to read 100% with the reactor at full power. Instead, all detectors are adjusted so that they read 100% × CPPF (if the reactor is at 100% of full power). Setting the reading to 100% takes care of the detectors reading low because of fuelling ripple. Increasing this by the CPPF preserves the margin to trip for the worst case scenario. Trips will occur early if the vulnerable channel is not the CPPF channel.

Poor fuelling can produce a high CPPF that results in a small margin to trip. When this happens, the NOP trips can seem very restrictive, with power well below any possibility of dryout or centerline melting. Keep in mind that for some particular slow loss of regulation accident there is a channel that could reach dryout just as the trip setpoint is reached.

If the channel ripple is higher than the CPPF because of some local flux distortion resulting from an unexpected device configuration (perhaps compounded by xenon effects) due, for example, to a shutoff rod stuck partly inserted into the core, trip coverage may be inadequate. The design basis set may include some of these highly unlikely device configurations that give extreme flux shapes. If these configurations require trip settings that are too restrictive in normal operation, they are protected by a hand-switch adjustment that reduces the trip setpoints. (The operator would need to recognize that he is in an abnormal configuration, reduce power appropriately, and adjust the hand-switch).

Inevitably, many possible reactivity device configurations are not in the design basis set. Another hand-switch setting that reduces the trip setpoints even further protects the associated flux shapes, the unanalyzed flux shapes. The analysts check that this trip setpoint provides coverage for a small bounding set of extreme flux shapes, not associated with any particular upset.

We end this section with one final comment about trip coverage. CANDU reactors with 37-element fuel reach dryout conditions before any bundle in the core reaches centerline-melting temperature. The thinner fuel elements (compared to 28-element fuel) provide more total surface area for cooling, and less thickness of uranium dioxide (UO_2 is a poor thermal conductor). CANDU reactors with 28-element fuel are much more likely to reach centerline-melting temperatures before any channel reaches dryout power. The 37-element bundle reactors are described as channel power limited, the 28-element bundle reactors as bundle power limited.

6.2.5 License Limits

An important supplement to the information in the previous section is that the ROP/NOP systems do not prevent the violation of license limits on bundle and channel power. For example, a typical license limit on channel power for 37-element fuel is 7.1 MW. The channel power that will produce dryout, assuming normal coolant conditions, is almost 30% higher than this. Obviously, in this example, a trip intended to prevent dryout may not prevent power increasing beyond the license limit.

The ROP/NOP trip ensures the integrity of the fuel channel by reducing power before there is risk of fuel disassembly that could pose a risk to the channel. An intact heat transport system guarantees that fission products released to the coolant will not reach the public. The bundle and channel power license limits arise from quite different considerations. Safety analysis demonstrates that radiation releases to the public is within stated limits, and shows adequate primary and backup trip coverage for a whole variety of different upsets. The analysis depends sensitively on the fuel power before the analyzed upset. Adequate trip coverage and protection of the public have not been demonstrated for operation with fuel power that exceeds the values assumed in the analysis; these values establish the license limits.

Operation with bundle or channel power above the license limits is operation with excessively high power. Enforcement of the license limits requires the joint efforts of the fuelling engineer, the fuelling crew, and the authorized staff. The fuelling engineer routinely checks the slow evolution of steady state bundle and channel powers with the off-line fuelling code. The code helps select channels for fuelling that provide an adequate margin to the license limits in normal operation.

How does the authorized staff know that a license limit has been violated? There is no direct measurement or panel indication, so the operator does not know unless told by the fuelling engineer. However, if the bulk power output is below the license limit and the flux is flat enough, and the fuelling engineer and fuelling crew have put bundles into the correct locations, then the bundle and channel powers will be within their limits.

This means routine monitoring of device positions and zone levels is part of the enforcement process for license limits on bundle and channel power. Conversely, if the flux shape is not standard, (an unusual tilt—e.g. with zones limiting, or rods stuck in core or some combination of rods giving an off normal configuration) then the operator has little choice but to assume that channel power limits (or bundle power limits) may be exceeded, unless analysis of the particular configuration demonstrates otherwise.

6.2.6 Bundle Power Monitoring

Individual fuel element and bundle powers are not measured. To ensure that the bundles are operating within their power limits (and therefore well below centre line temperature limits) at all bundle locations, we must monitor a parameter that is measurable - channel power. This is the sum of the thermal powers produced by all individual fuel bundles in a channel.

The actual measurement technique used to determine channel power varies as to whether or not boiling is allowed in the channels.

For a non-boiling channel

channel power = channel ΔT x channel flow x specific heat capacity of HTS D_2O

A sufficiently flat flux profile must also be ensured to prevent bundle power limits from being exceeded.

For a boiling channel

ΔT is no longer valid once boiling has commenced (because it will stay constant as long as there is some liquid in the channel). For this situation it is necessary to take account of the steam contribution at the channel outlet by either:

a) Inlet and outlet flow measurements, of a limited number of channels (FINCHs), is measured. A comparison of inlet and outlet volumetric flow rates determining the proportion of steam, and hence the enthalpy content at the outlet (i.e. the outlet flow volume will be larger than the inlet flow volume because the steam will occupy more space than water alone). A sufficiently flat flux profile must also be ensured to prevent bundle power from being exceeded. Note, once that flux shape is known, predictions of channel power and the outlet coolant quality in channels other than FINCHs can be made (with the aid of computer software).

b) i) At High Power

By measuring bulk thermal power and ensuring a sufficiently flat flux profile. The power of individual channels and bundles can be determined (again with the aid of computer software). Thus it can be ensured that channel and bundle power limits will not be exceeded.

ii) At Low Power (Non-Boiling Situation)

By the use of ΔT measurements across the reactor and, again, ensuring a sufficiently flat flux profile.

In all the above cases, the flux shape is assumed to be a normal (flat) shape. Generally, the liquid zone control system controls the flux shape within allowable limits, provided the liquid zones do not go out of their control range (individual zone control is phased out to ensure good bulk power control).

Off line computer simulations are used when necessary to determine accurate flux shapes and ensure that licence limits are not exceeded.

Our general concern therefore is to prevent the critical channel power, hence fuel channel dryout, from being reached.

We can meet our criterion in a non-boiling reactor by ensuring that under all analyzed neutron flux shapes, mass flow rates and HTS pressures, the outlet temperatures remain below saturation at all times. Initiating a reactor power reduction can ensure protection should any outlet temperature approach saturation temperature. Separate neutronic safety system trips will ensure that flux shape distortions will not cause any bundle overrating.

To prevent dryout in the boiling reactor, we ensure that flux shapes are known and channel power is monitored using channel flows (in a representative number of channels) and bulk power measurements.

Short-term local flux excursions will be indicated and corrected by RRS mechanisms (zones, adjusters, etc.). The operator is prevented, by a combination of design and procedures (defence in depth philosophy) from introducing sudden and drastic changes in neutron flux profiles.

6.2.7 Summary Of The Key Concepts

- The seven factors that contribute to the majority of fuel failures are manufacturing defects, fretting and erosion, stress corrosion cracking and hydride cracking, careless handling of fuel, overpowering, overrating and loss of sufficient cooling.

- These fuel failure mechanisms can be minimized by careful fuel bundle inspection before use, good housekeeping throughout the HTS, enforcement of all HTS chemical parameters, careful handling of fresh and spent fuel bundles, proper fuelling operations, moderate reactor power changes and monitoring of flows and temperatures while fuelling.

- There are limits on power to be extracted from a bundle or channel to prevent fuel overrating, hence preventing fuel failures due to the resultant overheating. These two limits are required to prevent overrating/overheating during operation with normal and abnormal flux shapes.

- Fuel overrating or inadequate cooling can cause high fuel temperatures.

Information available to the operator to ensure any bundle is not overrated is:

  - For a non-boiling reactor, by using channel outlet temperatures to measure channel power and ensuring a reasonably flat flux profile.

  - For a boiling reactor at high power, by using channel flows in a representative number of channels, using bulk power measurements and ensuring a reasonably flat flux profile.

  - Use channel outlet temperatures to measure channel power and ensuring a reasonably flat flux profile (for a boiling reactor at low power: non-boiling operation).

6.2.8 Detection And Location Of Failed Fuel

Failed fuel will inevitably release fission products (FP’s) into the Heat Transport System. The first two barriers in the prevention of fission product release will have been breached.

It is important that any failed fuel be detected, located and removed from the reactor as soon as possible for the following reasons:

a) Failed fuel will, especially under power maneuvers, release large quantities of FPs into the coolant. This will increase radiation levels to plant personnel and ultimately to the general public in the event of releases. This will also make the detection and location of future fuel failures more difficult due to the masking effect created.

b) Note that for the above reason, there is a shutdown limit for I^{131} in the HTS . The shutdown of the unit will result in lost power production.

c) In addition, leaving failed fuel in the reactor could worsen the situation. Channel blockage and damage to the pressure tube during defuelling could eventually result from distorted/disassembled fuel bundles. Debris in the HTS may contribute to future fuel failures.

Continuous and individual monitoring of all fuel bundles or fuel channels to determine and locate failures is not presently done at any CANDU location.

The usual method consists of first detecting the presence of a failed fuel element somewhere in the reactor and then locating it.

Various methods have been tried, over the years, to detect failed fuel. Some methods have proven to be more viable than others. All methods employed to date, however, have one feature in common, i.e. they all measure gammas or neutrons emitted by a Fission Product (FP).

These detection and location methods vary from station to station, but a basic description follows:

6.2.9 Detection of Failed Fuel

Sample analysis of D_2O from HTS using high-resolution γ detectors.

This will detect gross activity as well as specific γ energies from various isotopes (this is explained in more detail below). This can be accomplished by on-line Gaseous Fission Product (GFP) monitoring, which detects radioactive gases released from the fuel. This method will detect the presence of failed fuel only. This can also be accomplished by grab samples with lab analysis in the event that the GFP system is not available.

6.2.10 Location of Failed Fuel

Various methods have been used to locate failed fuel, but only two remain in general use.

a) Scanning of outlet headers/feeders.

Fission product solids, also known as Depositing Fission Products (DFPs), will be released from the failed fuel. In general the DFPs have limited circulation and tend to be deposited on sheaths, feeders, headers, etc. downstream of the location of the failure. Gamma detectors placed within the feeder cabinets can scan the outlet feeders for individual channels.

High activity on a given outlet feeder of a channel would indicate failed fuel in that channel. Thus, this method can be used to locate the channels containing the failed fuel.

b) Detection of delayed neutrons.

When the presence of failed fuel is indicated by the failed fuel detection system, sample lines from the outlet of individual channels can be scanned for the presence of delayed neutrons. These sample lines are long enough to allow the decay of γ and photoneutrons to reduce the background levels seen by the neutron detectors. Thus, the presence of fission product decay neutrons in a sample line indicates that there is failed fuel in that channel.

Detection and location are further complicated by the fact that the HTS always contains some fission products due to FPs deposited from previously failed fuel, and perhaps, the presence of trace quantities of uranium on the external surfaces of the elements (deposited during fuel fabrication). In addition, there may be an inventory of Activated Corrosion Products formed by the passage of crud through the reactor.

From the many fission products produced in the fuel, which radionuclides should be chosen to best complement the available detection instrumentation?

For failed fuel detection, radionuclides chosen for detection should have the greatest decay yield (production) possible and should be sufficiently volatile to escape easily from the failed fuel (such as noble gases). Because gases are not removed by the purification system, this gives better sensitivity to a monitoring system based on noble gases. Half-lives should be such that an equilibrium value (4-5 half lives) can be achieved in the HTS over a reasonable period of time (days). This permits detectable quantities to build up, even from a small leak.

Also, in practice, this biases the system heavily towards the detection of gammas rather then neutrons (since neutrons have a smaller decay yield).

For location using delayed neutrons, volatile delayed neutron emitters are observed. A half-life of slightly longer than the delay times used for the sample lines (for the decay of N^{16} and O^{19}) is desired. The short half-life ensures that the signal from the channel with the failed fuel will be higher than the signals from other channels, since the isotopes will decay before they have dispersed throughout the core.

For location using depositing fission products, the DFP must readily deposit itself on the feeder before dispersing throughout the HTS. Longer half-life will allow for the buildup of activity on the outlet feeders. The chief disadvantage of this system is that DFPs do not easily escape from the fuel.

This leads to a general conclusion:

Short half-life (<1 min) is most suitable for failed fuel location.

Longer half-life (hours-days) is most suitable for failed fuel detection.

The most recent CANDU generating stations use systems that monitor:

1) Specific γ energies from isotopes, typically Kr^{88}, Xe^{133}, Xe^{135}, I^{131} and total γ for failed fuel detection .

2) Delayed neutrons from Br^{87} or I^{137} for failed fuel location.

6.2.11 HT System Iodine Concentrations

The Station Licence imposes a limit on the quantities of fission products, usually referenced to I^{131} levels, which can be tolerated with the reactor in an at power condition. It is worth pointing out that with no failed fuel present, the level of I^{131} in the HTS is normally quite low. The continued presence of one failed fuel element under steady state reactor operation can increase this normal level by a factor of about four. Power transients however will increase the level of I^{131} in the coolant by a further factor of 10 to 50 times, ie, up to 200 Ci per failed element due to stressing of the defect.

For example, a typical inventory limit is 8 Curies I^{131} in the HT D_2O. This iodine limit is set primarily because of potential environmental releases, the in-plant consequences of high HT iodine concentrations are also important. In this case, iodine uptake by plant personnel due to HT D_2O leaks and subsequent iodine vapour release is the reason.

As a precaution against further increases of I^{131} at the action limit, reactor power should not be changed as this could make the defect(s) worse. HT purification flow should be maximized to remove the I^{131} as rapidly as possible from the HT D_2O. At the shutdown limit, the reactor should be shut down, the HT system cooled down and the HT purification flow rate maximized, until the iodine concentration is reduced. As mentioned earlier for any fuel defect, the defective bundle must be located and removed from the reactor.

Should the reactor be shutdown due to high levels of I^{131} in the HTS, the observed iodine will often increase (by up to a factor of 20 or so) following the shutdown.

This does not mean that more defects have been produced. What has happened is that more iodine has been released into the HTS coolant by the additional stressing of existing defects (due to temperature and pressure changes in the fuel pellets/sheaths on shutdown.

6.2.12 Summary Of The Key Concepts

- Failed fuel is removed from the reactor to:
- Reduce radiation levels in the HTS for plant personnel protection and protection of the public (in the event of a LOCA)
- Prevent fission products from entering the HTS
- Prevent channel blockage or pressure tube damage during defuelling
- Prevent a plant shutdown once shutdown limits of I^{131} in the HTS are reached
- Three general techniques for detecting and locating failed fuel are: sample analysis of D_2O from the HTS system, scanning of outlet headers/feeders and the use of high-resolution gamma or neutron detectors.
- The methods for detection of failed fuel use the detection of longer-lived fission product γs (either gross activity or specific

γ energies). Shorter-lived γs or delayed neutrons are used for failed fuel location.

- To reduce I^{131} levels in the HTS, power should be maintained steady to prevent making the defect worse, purification flow maximized and the defective fuel located and removed.
- I^{131} concentration may increase because shutdowns could make the defect worse from thermal and mechanical stressing.

6.3 Fuel Handling

The operating life of a CANDU reactor can be divided into three distinct periods from the point of view of fuel management:

1) The period from first criticality when the reactor is loaded only with fresh fuel to the onset of fuelling

2) The period from the onset of fuelling, necessary to maintain the reactor critical, to the final or equilibrium core state

3) The equilibrium period, which is characterized by a relatively stable distribution of the overall core power and burn-up. This equilibrium period covers most of the reactor life.

It is this last period that we are interested in with regards to fuelling criteria.

This section will discuss fuelling considerations, channel blockage detection while fuelling and handling and storage of irradiated fuel.

6.3.1 Fuelling Considerations

The Fuelling Engineer provides a fuelling list specifying the channels to be fuelled. Computer programs, SORO or RFSP (Simulation Of Reactor Operation/Reactor Fuelling and Simulation Program: station dependant) produce this list. The channels to be fuelled are determined on the basis of such factors as:

- Power distribution,
- Zone levels,
- Fuel burnup,

- Fuelling Ripple (Ripple - the ratio of actual channel power to a reference channel power), position of reactivity mechanisms, number and types of fuel bundles last inserted in the core, etc.

Only channels that appear in the fuelling list may be fuelled.

While in general the information provided by SORO/RFSP is valid, changes in the core conditions may have occurred since the simulation was performed. These changes would require that SORO/RFSP be run again to provide updated information. Depending on the station, these programs are run a minimum of three times per week, and more often when core conditions are changing, i.e. adjusters driving etc.

The following are considerations used for the selection of channels to be fuelled:

1) Higher burnup channels shall be fuelled first. The reason is that in these channels the fuel is depleted and reactivity is low. Higher burn-up channels are underpowered, and should be fuelled preferentially.

2) Reactor power distribution shall be kept symmetrical. Asymmetry in power distribution increases the load on the Reactor Regulating System (RRS) which has to maintain a zone reactivity balance. This increases the probability of a reactor trip (Neutron Overpower / Regional Overpower Trips will occur if a zone power is too high). To achieve axial flux symmetry, equal number of channels shall be fuelled from each end of the reactor. To achieve radial (and azimuthal) symmetry, proportional numbers of channels shall be fuelled in each zone controller region.

3) The channels with the largest reactivity gain on fuelling may be selected if the overall core reactivity is low.

   The core reactivity is maintained by compensating the reactivity loss due to fuel burn-up with the reactivity gain due to fuelling rate. When the fuelling rate cannot be maintained, it is necessary to fuel channels with high reactivity gain on fuelling, i.e. high burnup channels in the innermost part of the core.

   If margin to trip is low for such a high reactivity gain channel, two actions may be taken:

  - Derate (or be prepared to derate) the reactor,
  - Prior to fuelling, calibrate the NOP/ROP (neutron overpower/Region overpower) detectors to restore the appropriate margin to trip.

4) The channels to be fuelled should not have known abnormal conditions that will hinder fuelling, such as closure plug or seal face problems. This means the fuelling machine may have problems attaching to the channel, sealing against the channel, reseating the channel closure, etc. These conditions could cause a unit to be shutdown for repairs.

5) Defective fuel bundles shall be removed as soon as possible. Fission product releases to the HTS must be prevented.

6) Avoid fuelling channels close to recently refueled channels. Excessive fuelling in one region of the core may lead to high fuel bundle powers (due to high neutron flux), leading to overheating and fuel failures.

7) There shall be no fuelling with control absorbers (CAs) in the core. CAs drop in the core only during abnormal operating conditions (such as reactor trips or stepbacks). Fuelling operations are to be performed only during normal operating conditions, i.e. reactor operating at a steady power level.

   During fuelling operations, reactivity changes should be avoided, i.e. poison removal/addition, moving adjusters, etc. Adjuster position imposes no restriction on fuelling. This is to ensure that the actual effects of fuelling are observable.

   Fuelling operations shall not take place during reactor power increases.

   During the transients mentioned above, xenon transients will occur. This can result in the formation of flux tilts. As discussed in the preceding module, flux tilts can cause bundle overheating and/or bundle overpowering. With the addition of the positive reactivity of a new fuel bundle, the previously mentioned problems are compounded, and hence must be avoided.

8) All factors being equal, in practice the channels with low zone levels should be fuelled first. Fuelling zones with high

levels can possibly cause flooded zones, and therefore, ineffective flux tilt control. Liquid zone levels must be kept within their correct operating range.

The fuelling list provides for more channels to be fuelled than scheduled. Hence, the control room staff are allowed some choice in the selection of the fuel channels for items 4 through 8 on the list above.

6.3.2 Preferred Operating State during Refuelling

The preferred state during refuelling operations is with the reactor critical and operating. The reasons are that:

a) RRS is functional with the reactor critical. It can detect, and immediately compensate for changes in reactivity to limit possible overpower transients. When the reactor is subcritical, the reactivity insertions are not observable. This could cause the reactor to go critical earlier than expected, when a reactor restart is initiated.

b) Additionally, if fuelling is performed while the unit is shut down, there may be no indications of flow blockage.

c) Zirconium under irradiation becomes brittle, and is even more brittle when cold. This increases the chances of fuel damage to handling.

However, we should remember that performing on-power fuelling does present some operational concerns such as:

1) Opening the HT system pressure boundary (potential for a LOCA)

2) Insertion of a foreign object in the channel (possible flow blockage causing fuel overheating)

3) Local flux distortions (place demands on RRS)

Refuelling of the reactor in any state other than the preferred state requires approval beyond the authority of the Shift Manager.

6.4 Summary Of The Key Concepts

Considerations used to select channels for fuelling are:

- Channel abnormal conditions, to ensure that the fuelling process can safely take place

- Defective fuel in the core must be removed to prevent releases to the HTS

- Proximity to recently fuelled channels, to ensure that bundle overpowering and overheating does not occur

- Abnormal operating conditions, to ensure that bundle overpowering and overheating does not occur due to the influence of Xe transients

- Channel burn-up, to ensure channels are not under-powered

- Power distribution, to ensure that zone reactivity balance is maintained

- Reactivity gain, to ensure the reactor can remain critical

- Liquid zone levels, to ensure that liquid zones remain within their control range

- The preferred state for fuelling the reactor is with the reactor critical and the unit operating. This allows RRS to detect and compensate for changes in reactivity. While shut down, flow blockage detection may also be unavailable. Also, zirconium is brittle when cold, which makes fuel damage due to handling more likely.

- Authorization must be obtained for fuelling in any other state than the preferred state.

6.4.1 Channel Blockages

One of the concerns while fuelling is channel blockage. The chances of a channel blockage during refuelling are increased due to the insertion of fuel, rams etc. into the channel. If a blockage occurs, coolant circulation is reduced, with the potential for fuel overheating. This could result in fuel damage and release of fission products to the HTS.

A flow blockage in a channel can be determined in a number of ways:

1) If the channel being fuelled is a fully instrumented channel, direct flow indication is available. A flow blockage would be directly seen as a reduction of flow. As very few channels are fully instrumented, (no fully instrumented channels are installed in some CANDU units) other methods of flow blockage detection are required for the other channels.

2) The channel outlet temperature is measured for each outlet feeder pipe. This is performed with RTDs (Resistance Temperature Detectors). During fuelling, many changes in channel flow and temperature will occur. Some of these changes occur due to shield plug removal, fuel carrier and ram insertion into the channel and fuelling machine cooling effects and flows. If channel outlet temperature rises more than expected (as compared to a routine fuelling operation), it is likely that a cooldown flow reduction has occurred.

   Of course, this method is only valid for non-boiling channels, since channel outlet temperature will not increase above saturation temperature corresponding to HTS pressure. (One note to make here is that for some CANDU units with boiling channels, cool D_2O is injected by the fuelling machine to take a boiling channel out of boiling while being fuelled. This allows the channel ΔT to be used for flow blockage detection during fuelling.)

3) For channels in boiling, a method of determining if a flow blockage has occurred is by monitoring ΔP across the channel (measured on the fuelling machines). The measurement of coolant ΔP across the channel will correspond to a certain coolant flow. If the ΔP changes dramatically, a flow blockage has likely occurred. The change in ΔP will indicate the location of the blockage.

   - For example, if the ΔP across the channel decreases dramatically, a flow blockage has likely occurred in the inlet or outlet feeder. Say there is a 95% flow blockage in the channel inlet feeder. The reduced flow will reduce frictional losses in the channel and feeders. The pressure at the channel outlet will be very close to the outlet header pressure. The pressure at the channel inlet will not be as influenced by the inlet header due to the blockage, hence channel inlet pressure will also approach the pressure at the channel outlet. As you can see, the ΔP across the channel has decreased (ΔP will approach zero as flow reduces). Similarly, a channel outlet feeder blockage will cause pressures to approach the channel inlet pressures, and have a similar decrease in channel ΔP.

- For example, if the ΔP across the channel increases dramatically, a flow blockage has likely occurred in the channel. Say there is a 95% flow blockage in the channel. The reduced flow will reduce frictional losses in the channel and feeders. The pressure at the channel outlet will be very close to the outlet header pressure. The pressure at the channel inlet will be very close to the pressure of the inlet header. As you can see, the ΔP across the channel has increased (ΔP will approach the inlet to outlet header ΔP as flow reduces).

Detection of a flow blockage on each channel during operation is not practical, since blockages during operations, other than fuelling, are unlikely. Detection is especially difficult if the channel is a boiling channel, in which a blockage would be detected by a flow verification procedure. In this procedure, the reactor output is periodically reduced, reducing the channel outlet temperatures below the saturation temperature. At that point of the procedure, the channel outlet temperatures will be checked that they are reading correctly and that they respond to the changes in reactor power. If no changes are occurring, or the temperature remains at saturation temperature, a flow blockage may be suspected. Corrective actions will be required (i.e. verify channel conditions with fuelling machines, attempt to clear a blockage, reduce power further, shutdown, etc.)

6.4.2 Handling Irradiated Fuel

Irradiated fuel discharged from the reactor continues to produce significant amounts of heat. A fuel bundle produces a few kW of decay heat for several hours following discharge. For example, a typical irradiated fuel bundle produces about 10 kW of heat 1 hour after discharge. Natural air-cooling can remove only 1kW of this heat . If the decay heat is not removed, the sheath will deteriorate due to high temperature oxidation.

An irradiated fuel bundle is extremely radioactive. For example, the dose rate 1 metre from a typical bundle in air is ~100 000 rem/hr after 1 day following discharge. A 20-second exposure at 1 metre would result in a dose of 600 rem, which is for all practical purposes, lethal. Obviously, protection against such high doses is also necessary.

For these two reasons, the irradiated fuel shall be adequately cooled and shielded at all times. Therefore, adequate cooling and shielding are provided during the residence time of the fuel bundles, both within the fuelling machine and during the transfer process to the irradiated fuel bay.

At some point in the fuel handling process, while transferring the fuel from the fuelling machine to the irradiated fuel bay, the fuel bundle may be exposed to air. However, this happens for a short while only (minutes at the most) and will not result in a fuel failure if cooling is resumed.

As mentioned earlier, another concern about irradiated fuel is that the sheath becomes brittle with irradiation and is particularly brittle when cold. Special care should be exercised in handling irradiated fuel throughout the fuelling process.

6.4.3 Handling Failed Fuel

Particular problems are encountered when handling failed fuel bundles due to the potential for spread of contamination.

Fuel bundles can fail while in the core, or during the fuel handling process. The detection and location of failed fuel has been described.

As mentioned above, at some point in the irradiated fuel handling process, the fuel bundles may be exposed to air. At this point, airborne particulates and iodine samples are taken to determine the presence of failed fuel. When airborne sample fields increase a couple of times over their normal values, failed fuel is suspected. This can be used to identify a failed bundle or at least narrow the failures down to a pair of bundles. Monitoring during the defuelling process could also be used to attempt to identify the failed fuel bundle(s).

In most stations, the failed fuel is processed normally and sent to the Irradiated Fuel Bay (IFB). In some stations the defective fuel is left in the fuelling machine while it still clamped onto the reactor. This allows the HTS purification circuit to remove a large portion of the escaping fission products.

In the IFB, the failed bundle will be identified/examined and can be stored in specially designed failed fuel cans, or, for small defects, can be stored with the rest of the irradiated fuel.

6.4.4 Monitoring the Irradiated Fuel Bay

The irradiated fuel is extremely radioactive and hot. Both the radioactivity and heat are caused mostly by the decay of fission products.

The radioactivity of irradiated fuel bundles is mainly γ. There is a lot of α activity (from the products of the U_{238} decay) and β activity (from the decay of fission products) in the bundles, but both particles are short range and absorbed within the bundles. As mentioned previously the γ from a fuel bundle after 1 day will be ~100 000 rem/h at 1 metre. Even after longer periods, these γ fields can be very high (1 000 rem/h @ 1 metre after 1 month, 10 rem/h @ 1 metre after 1 year).

The decay heat is also quite significant. Remember that a typical fuel bundle produces about 10 kW of decay heat 1 hour after discharge. Even after 2 weeks, the decay heat production will be approximately 1 kW. This heat input for the IFB could be very high when the reactor has to be completely defuelled as in the case of an accident. (Note that long term cooling requirements are not as demanding, as decay heat from a bundle after 1 year will be ~1Watt.)

It is clear then that the IFB should provide adequate shielding and cooling at all times. The IFB is filled with demineralized water because demineralized water does not contain suspended or dissolved impurities. This minimizes corrosion of the fuel and IFB systems and keeps the IFB clear to allow for the inspection and handling of the fuel. The demineralized water in the IFB provides the following:

- Shielding against radiation
- Cooling medium to remove decay heat
- Purification circulation

Shielding against gamma radiation is best provided by heavy elements, like lead. However, the same amount if shielding can be provided by sufficient thickness of lighter elements. Therefore, a few meters of water act as a very efficient shield . Equivalent shielding is provided by 8mm of lead or 98mm of water for gamma energy of 1 Mev. These thicknesses will reduce fields by half

The IFB cooling system should be able to remove all the decay heat from all the fuel bundles stored. This IFB cooling circuit is composed of circulation pumps, HXs, inlet and outlet headers. Sufficient redundancy is provided for reliability purposes.

The following parameters are monitored for the IFB water:

a) To maintain water purity, a small portion of the total inventory is passed through the purification circuit. The role of the purification circuit is to remove suspended solids, to reduce dissolved solids, and to remove corrosion products (including contaminants brought into the IFB on the transferred bundles). These substances can foul the components of the circuit. The purification circuit also serves to remove the excess water in the IFB and route it to the active liquid waste system. The circuit consists of skimmers, pump(s), filters, and IXs.

   The conductivity and turbidity in the IFB are monitored to ensure that the concentration of impurities are acceptably low. When these parameters exceed their upper limits, filters and IX resins shall be replaced.

b) The temperature of the IFB shall be monitored and maintained within limits, typically around 30°C. If the IFB water exceeds the limits, the IFB walls can be damaged (in some stations an epoxy liner is used, which can be damaged by high temperature and rate of temperature change). Throttling the LPSW valves on the secondary side of IFB HXs automatically performs temperature control.

c) The water in the IFB shall be maintained at a level high enough to provide adequate shielding. If the water level is too low, the shielding will not be sufficient. If the water level is too high, it causes diversion (at the IX column outlet) of cleaned water to the active liquid waste system. Therefore, the water level should be monitored and controlled. Level control is achieved with an upper and lower level switch. If the level is too low, the make-up demineralized water valves open more. If the level is too high, the IX effluent valves open more.

d) The flow of IFB water through the cooling and purification circuits is monitored and controlled to ensure that cooling and purification requirements can be met.

The IFB room is provided with a ventilation and filtration system to remove radioactive particulates and exhaust the gases. The failed fuel in the IFB will release fission products that can contaminate the IFB. Gas bubbles rising to the surface of the water indicate the release of gaseous fission products, and therefore, the presence of radioactive gases in the IFB is monitored (the IFB has area γ monitors, as well as monitoring the exhaust for gross activity). Hydrazine can be added to suppress the release of gaseous fission products from the IFB water surface. This gives the IFB purification system more time to remove them since hydrazine will combine with radioiodines and form chemical products which are less volatile and more soluble in IFB water.

6.4.5 Summary Of The Key Concepts

- Flow blockages can be detected by fully instrumented channel flow indications, channel outlet temperatures for non-boiling channels and ΔP measurements for boiling channels.

- Irradiated fuel requires shielding and cooling at all times. Care must be given to physical handling of the fuel because the sheath has become brittle.

- In most cases, defect fuel will be placed in specifically designed canisters for storage to minimize the spread of contamination.

- IFB water is monitored for temperature, flow, level and purity.

- The IFB atmosphere is monitored for radioactive gases. These gases indicate the presence of failed fuel.

6.5 ASSIGNMENT

6.5.1 Fuel Performance

1. State the 6 factors that contribute to the majority of fuel defects.

2. List methods that can be used to reduce fuel failures.

3. Explain 2 factors that can cause fuel to overheat.

4. Explain the reason for placing limits on fuel bundle and fuel channel power.

5. State the indications the control room staff have for ensuring a bundle in not overpowered.

    a. In a boiling channel (2)

    b. In a non-boiling channel (1)

6. Describe how a reference flux shape is obtained for a CANDU reactor.

7. Explain why the reference flux shape is never really obtained in an operating CANDU reactor.

8. Describe the effect on the flux shape when fresh fuel replaces high burnup fuel in a CANDU reactor operating at high power.

9. Define the following terms as they apply to a CANDU reactor;

    a. fuelling ripple

    b. channel peaking power factor

10. State three units used to measure fuel burnup.

11. Describe how the ROP scheme protects the fuel from dryout.

12. State how the fuel is protected against dryout when the adjusters are out of the core.

13. State how the control room staff know that no bundles are over rated.

14. State three reasons for removing failed fuel from a reactor.

15. Explain how failed fuel is detected in a reactor.

16. Explain two methods used to locate failed fuel in a reactor.

17. State three methods of reducing the I-131 concentration in the HTS.

18. Explain why the I-131 concentration in the HTS may increase when the reactor is shutdown.

6.5.2 Fuel handling

19. Explain why the following factors are used to determine if a pre-selected channel can be fuelled.

    a. Channel abnormal conditions

    b. Defective fuel in core,

    c. Proximity to recently refuelled channels,

    d. Abnormal operating conditions,

    e. Channel burn-up,

    f. Power distribution

    g. Reactivity gain,

    h. Liquid zone levels,

20. State the preferred reactor state for refueling and explain why this is the preferred state.

21. State three methods of determining if a fuel channel is blocked during fuelling.

22. Explain three major concerns when handling irradiated fuel.

23. Explain on additional precaution that is taken when handling irradiated fuel.

24. Explain four parameters monitored in the irradiated fuel bay.

25. List four parameters monitored in the spent fuel bay water. Explain the importance of monitoring each parameter.

26. State the parameter monitored in the irradiated fuel bay atmosphere

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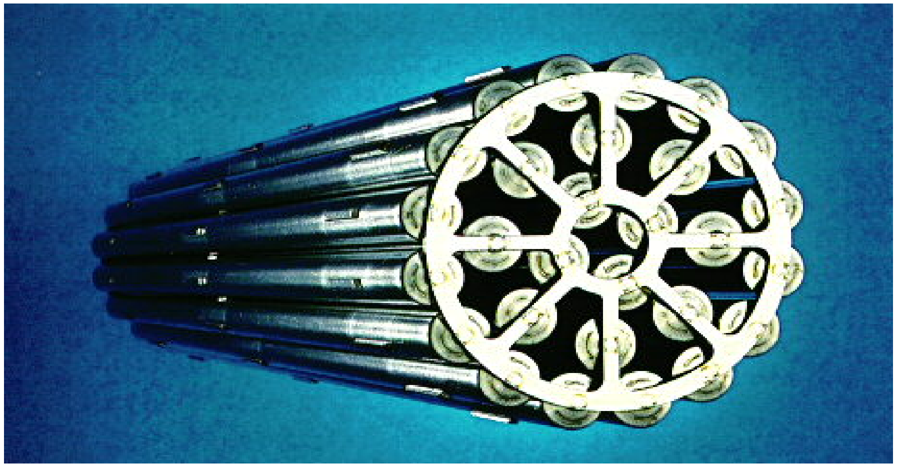
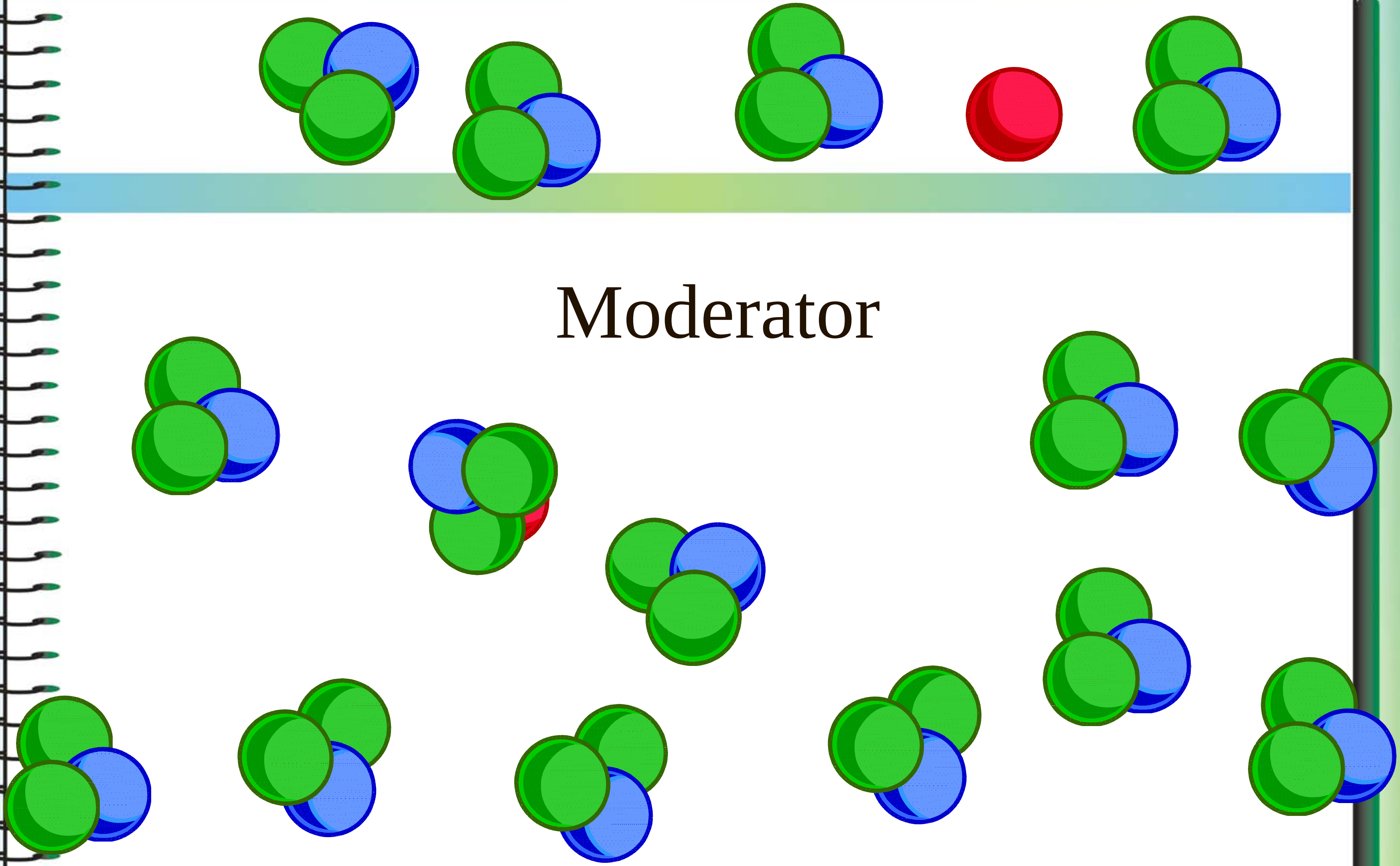
Intermediate Reactors and Auxiliaries

Safely Making Power



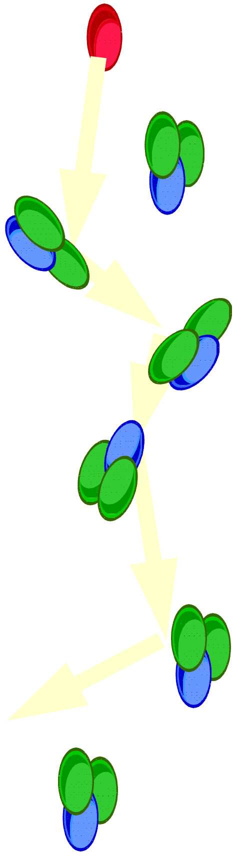


Moderator

Low Isotopic

- Indications
  - Acute zones drain
  - Chronic routine testing
- 0.1% downgrading adds –3.6 mk
- Adjusters can be removed only if the power is reduced
- 0.3% about the maximum downgrading possible and remain critical

Reactor Shutdown Guarantee



- **Over Poisoned (OPGSS)**
  - **Hundreds of mk of negative reactivity**
  - **Purification off**
  - **Sources of clean water isolated**
  - **Continuous circulation**
  - **pH and concentration checked regularly**
- **Moderator Drained**
  - **Moderator removed to storage**
  - **Water sources isolated**
  - **Drain in calandria guaranteed open**
    - **(Pickering A has dump tank)**

Temperature Control

- Outlet temperature about 61 degrees
- Because of flow paths there are warmer places in the reactor
- Why is it important?
  - Accident mitigation
  - Neutronic considerations
  - Explosion Hazard
  - Metallurgy Considerations

Moderator Level

- Most reactors the calandria is full into the relief ducts
  - Minimize leakage
  - Cool components
  - Pickering ‘A’ can change level to control power
- High Level
  - Insufficient space for water from SDS2
- Low Level
  - Negative reactivity at top of core
  - Overheating
  - Increased D_2 evolution
  - May affect ion chambers

Abnormal Conditions

- Loss of cooling
  - Moderator temperature increases
  - Reactor trip or power reduction to prevent aforementioned problems
- Heat Exchanger Leak
  - In Hx moderator pressure is greater than service water
  - Small leaks are to the lake
  - Economic penalty of downgraded D_2O greater than safety concerns with a small leak
  - Leaks require shutdown to repair.

Cover Gas

- Explosive Limits
  - 8% D_2, 5% O_2
- Normal
  - <1% D_2, enough O_2 to ensure recombination
- Purging
  - Compressors out of service
  - High concentrations of D_2
  - High concentrations of N_2

Monitoring

- On line gas chromatograph
  - Continuous monitoring of D_2, O_2 & N_2 at a number of points
- Laboratory Samples

Abnormal Conditions

- High concentration of D_2 (2%-4%)
  - Purge cover gas
  - Add O_2
  - Put in second compressor
  - Check recombination unit
  - Lower moderator temperature
  - Increase moderator level
  - Increase purification flow
  - No increases in reactor power

D_2 Concentration > 4%

- Do the things listed previously
- Confirm
- Shutdown

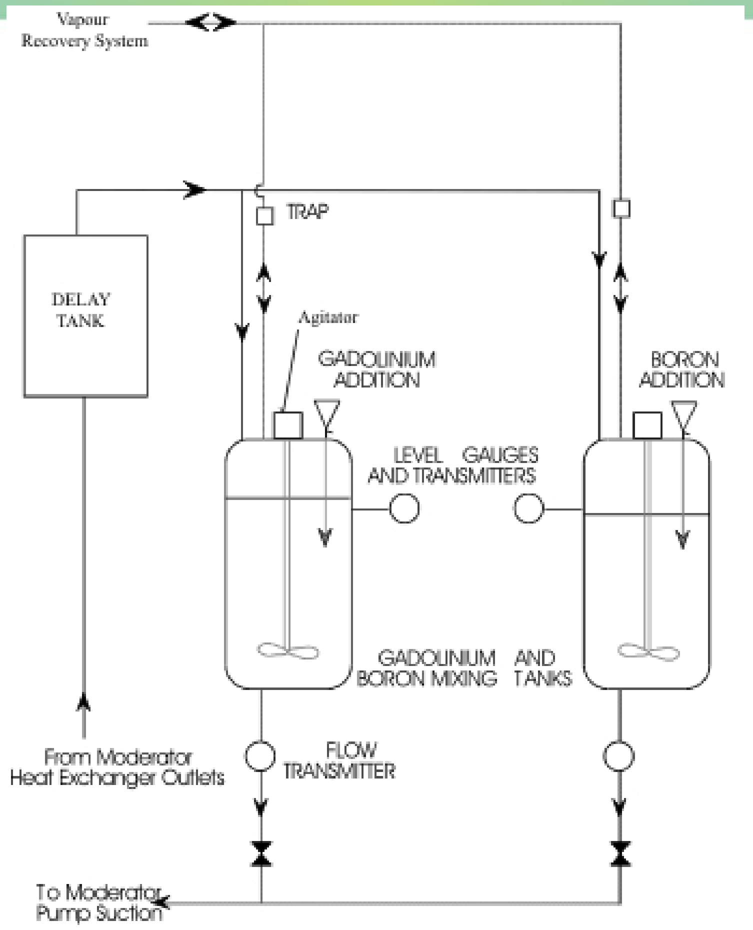
High N_2

- Nitric acid formed by radiolysis
  - Increased D_2 production
  - Corrosion
- Removal
  - Purging
  - Increase moderator purification to remove acid

Poison Addition

- Reasons for poison
    - Fresh fuel
    - Compensate for lack of Xenon
    - OPGSS
    - To compensate for over fuelling

Poison Addition System



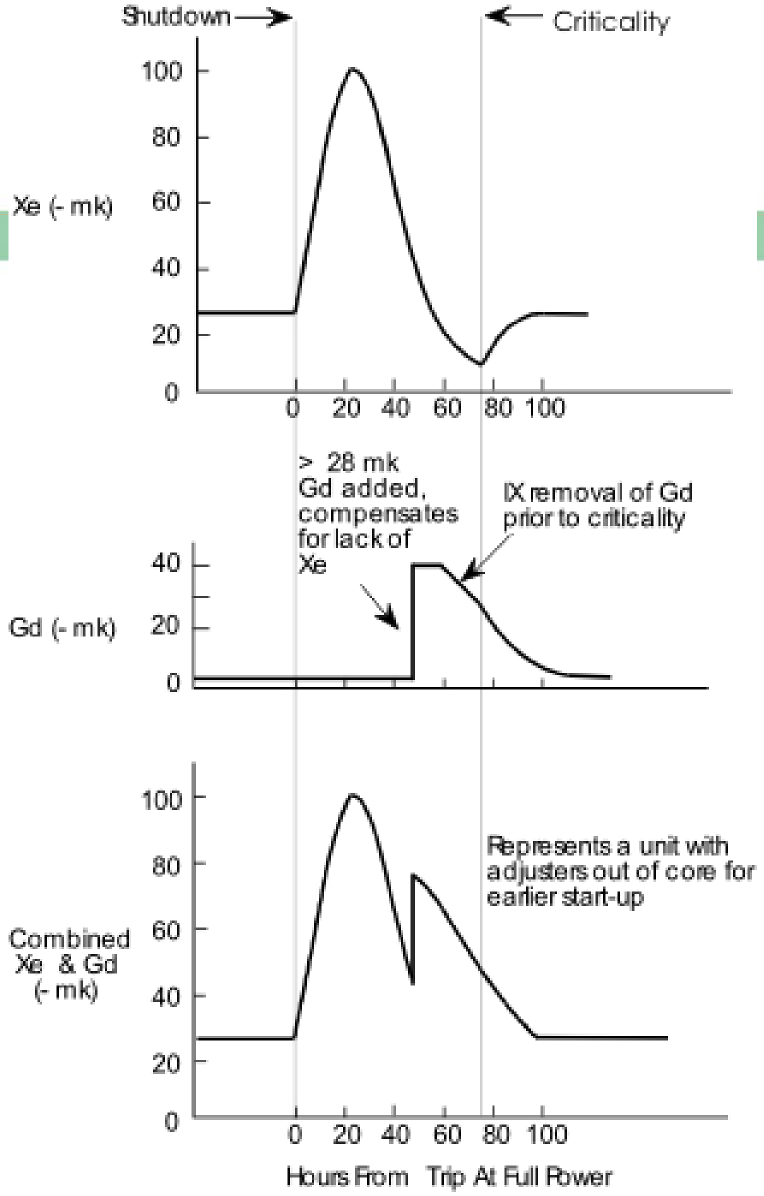
Boron as a Poison

- Good
  - Slow burnout
  - Smaller mk/kg if added inadvertently
  - Lower conductivity less D_2

- Bad
  - Low solubility
    - Blocked lines
  - Hard to remove
    - Lots of IX resin

Gadolinium as a Poison

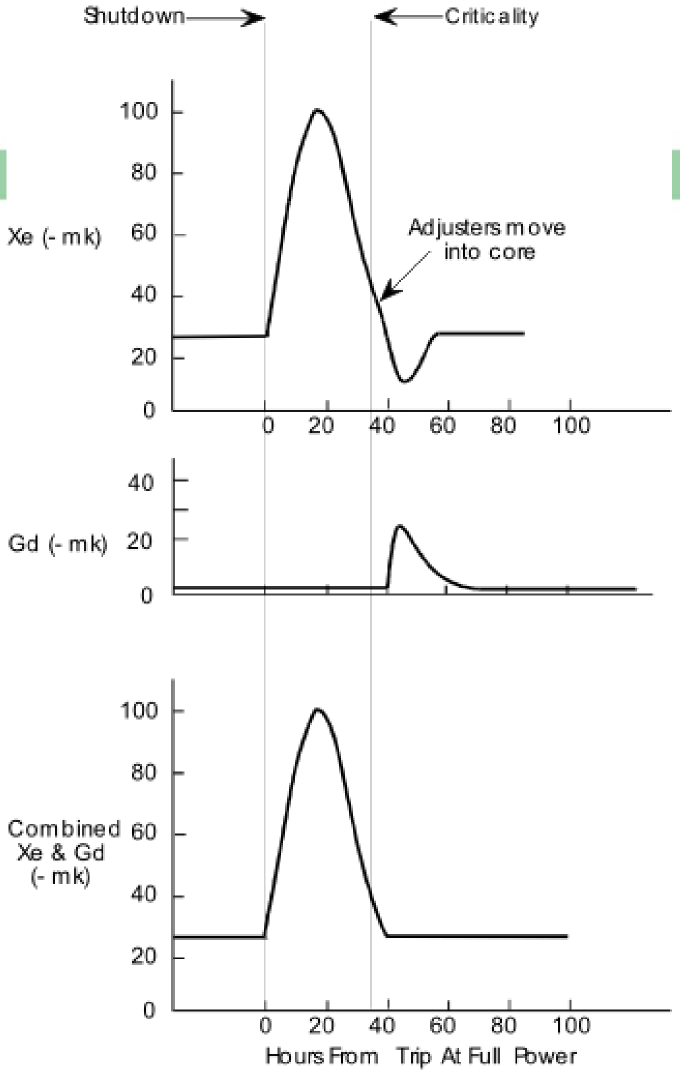
- Good
  - Fast burnout
  - High solubility
  - Easy to remove
- Bad
  - High conductivity
  - Rapid insertion of –ve reactivity if added inadvertently
  - Will precipitate if pH>7



> 28 mk Gd added, compensates for lack of Xe

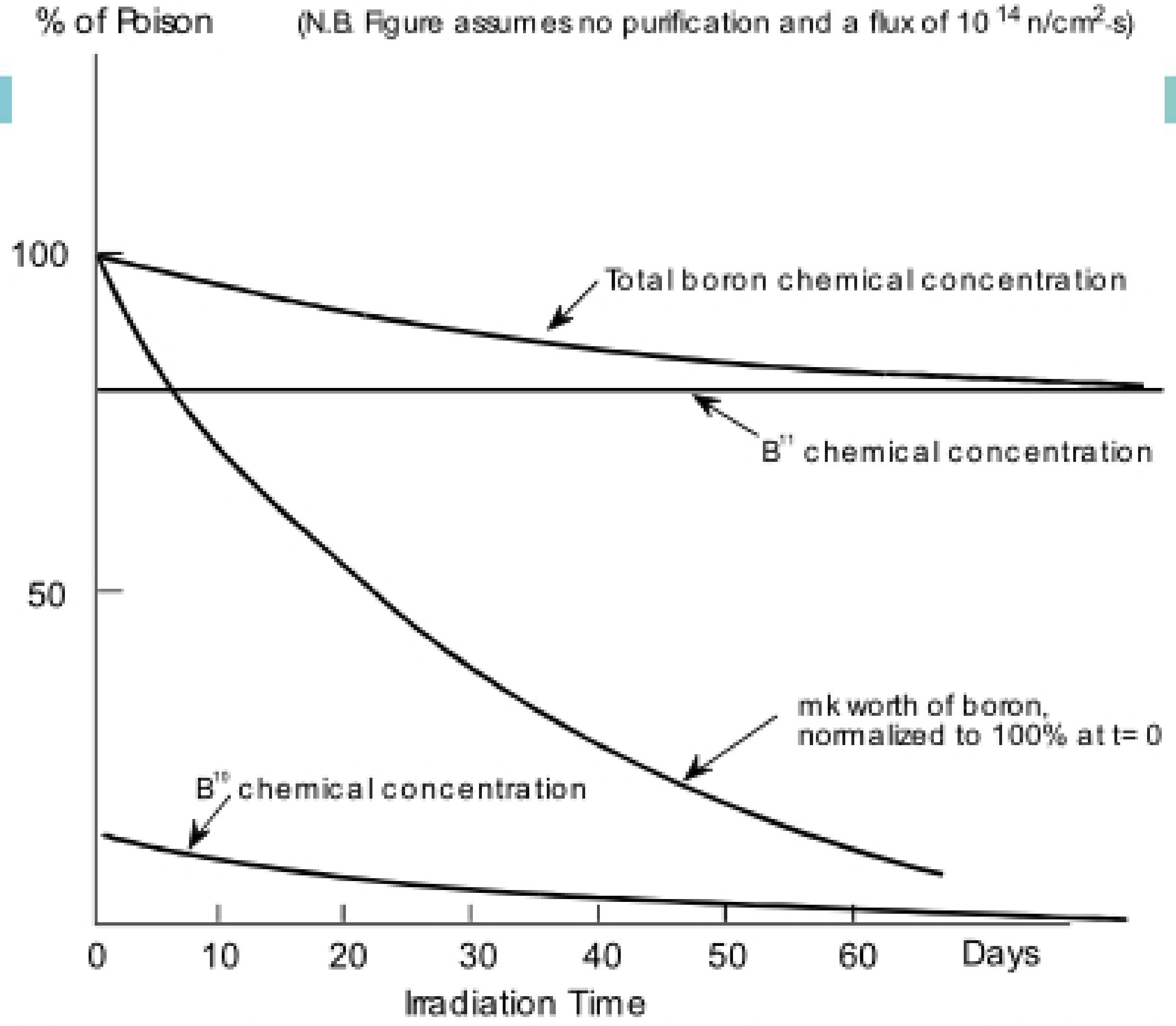
IX removal of Gd prior to criticality

Represents a unit with adjusters out of core for earlier start-up

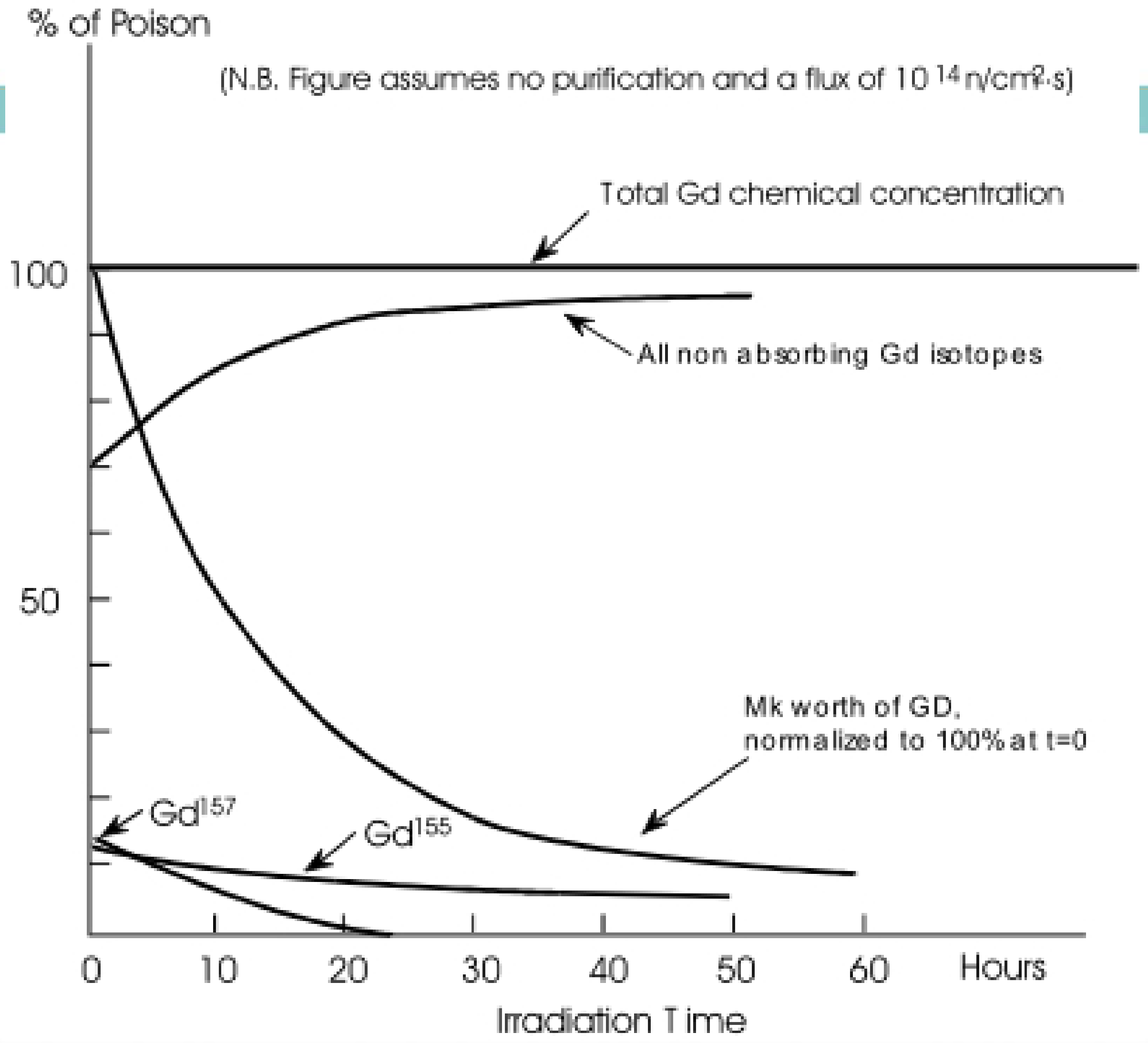

Shutdown
Criticality
Xe (- mk)
100
80
60
40
20
0
Adjusters move into core
0
20
40
60
80
100
Gd (- mk)
40
20
0
Combined Xe & Gd (- mk)
100
80
60
40
20
0
0
20
40
60
80
100
Hours From Trip At Full Power

Monitoring Poison Load

- Chemical concentration when shut down
  - Chemical concentration is not an indicator at power
  - Different isotopes have different cross sections
- Zone level when at power



(N.B. Figure assumes no purification and a flux of 10^{14} n/cm^2-s)


(N.B. Figure assumes no purification and a flux of 10^{14} n/cm^2·s)

RRS Control

- Auto Gd addition
- Power rising
- Zones and rods not controlling
- Defence in Depth

Abnormal Conditions

- Inadvertent addition at power
  - Zones lose control
  - Exceeding poison limit
  - Poison outage
- Inadvertent removal at power
  - Zones lose control
  - Absorbers drive in
  - Auto addition

More Abnormal Condition

- Inadvertent removal at start up
  - Unexpected criticality
- Boron used instead of gadolinium
  - Increase poison removal time
  - Burn out slower
  - Cost of removal by IX greater
- Poison Unavailability
  - Some operations difficult or impossible

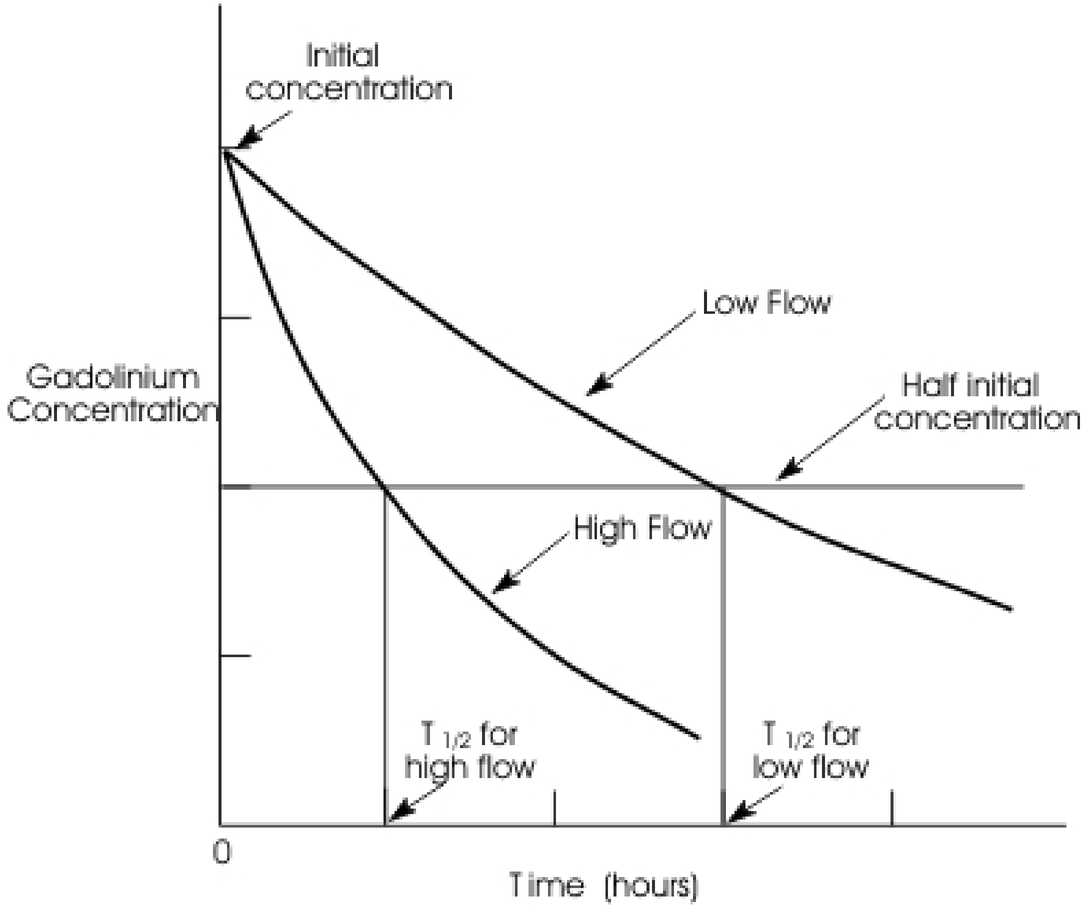
Purification

- Keep moderator pure
  - Minimize D_2 hazard
  - Low corrosion
  - Low neutron absorption
- Control pH
- Strainers
- IX columns

Normal Clean Up

- Strong ions removed by column
  - Chloride
  - Nitrate
  - Gadolinium
  - Most radionuclides
- Boron is not removed as effectively as it is a weak ion

Gd Removal


Initial concentration
Low Flow
Half initial concentration
Gadolinium Concentration
High Flow
T 1/2 for high flow
T 1/2 for low flow
0
Time (hours)

Boron Removal

- Ion is weak
- Exchanges ions with the water
- Column removing boron saturates
- Each column reduces poison to about 1/7 of its original value
- Removal rate depends on
  - Flow rate
  - Mass of moderator water
  - Temperature of column
    - Increases temp decrease the equilibrium concentration

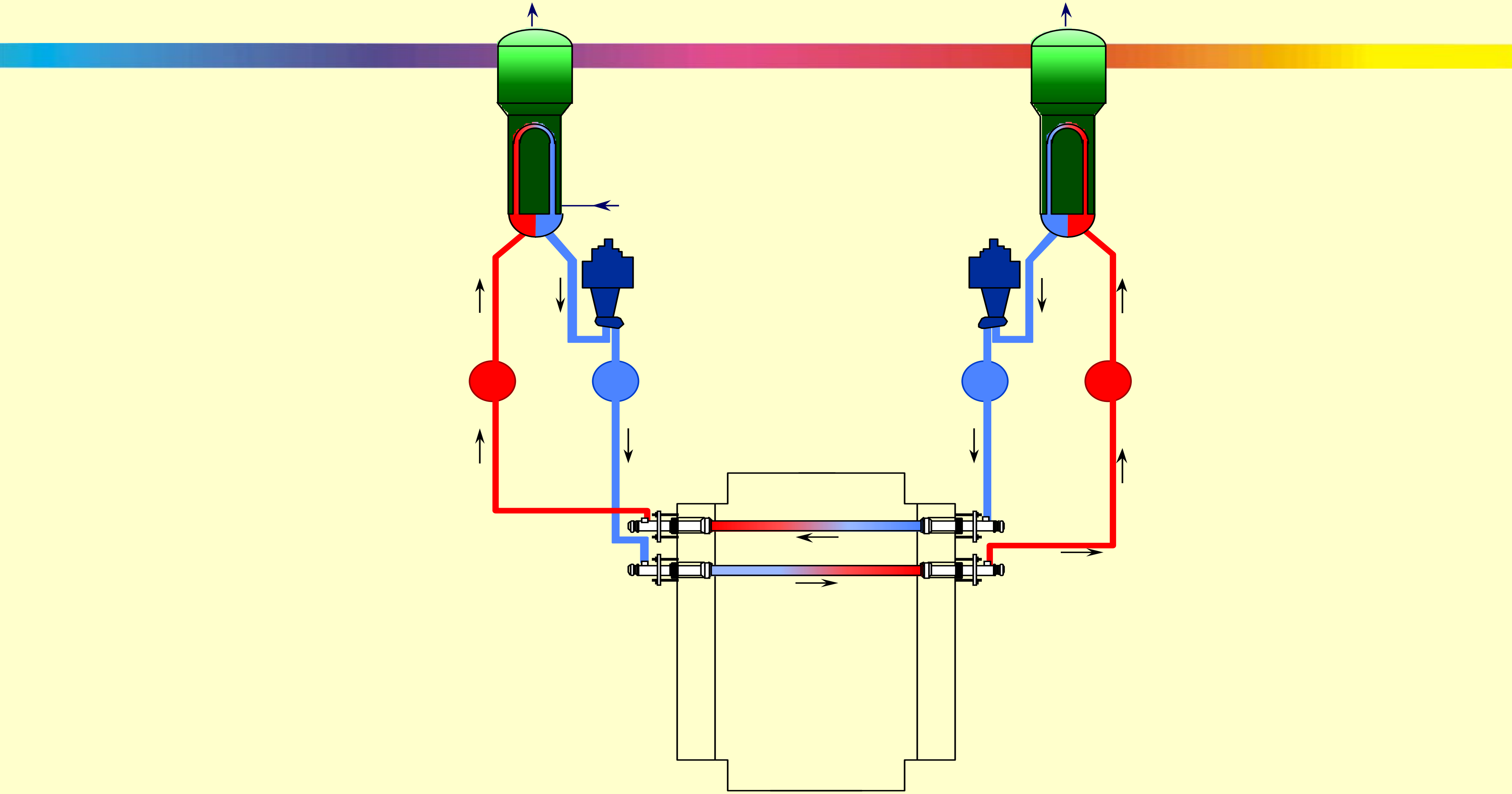
Operating Parameters

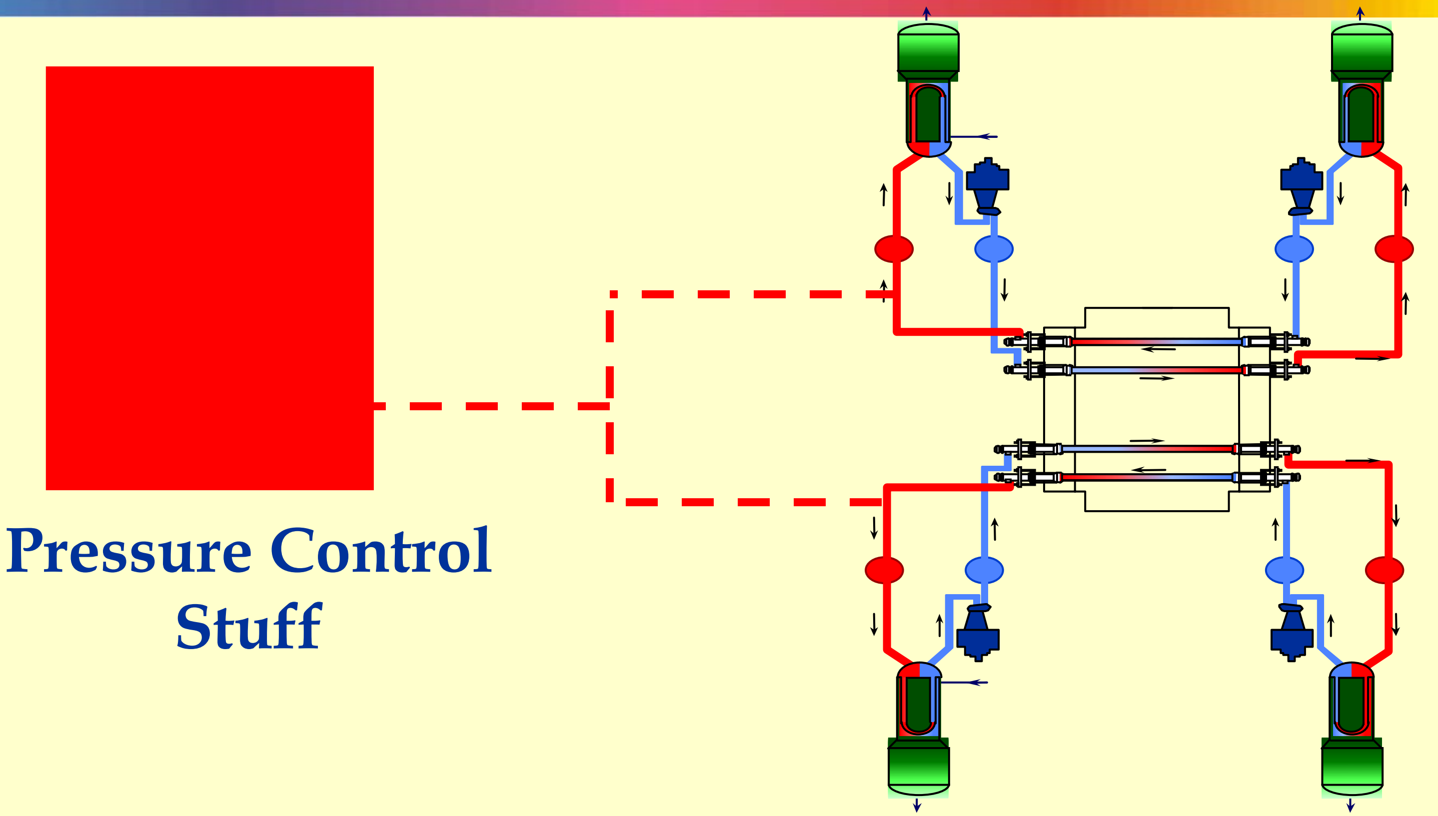
- Flow
- Temp
- Pressure
- Conductivity
- Spent columns
  - Check ΔP across column
  - Zone level
  - Increase chloride rate

GSS

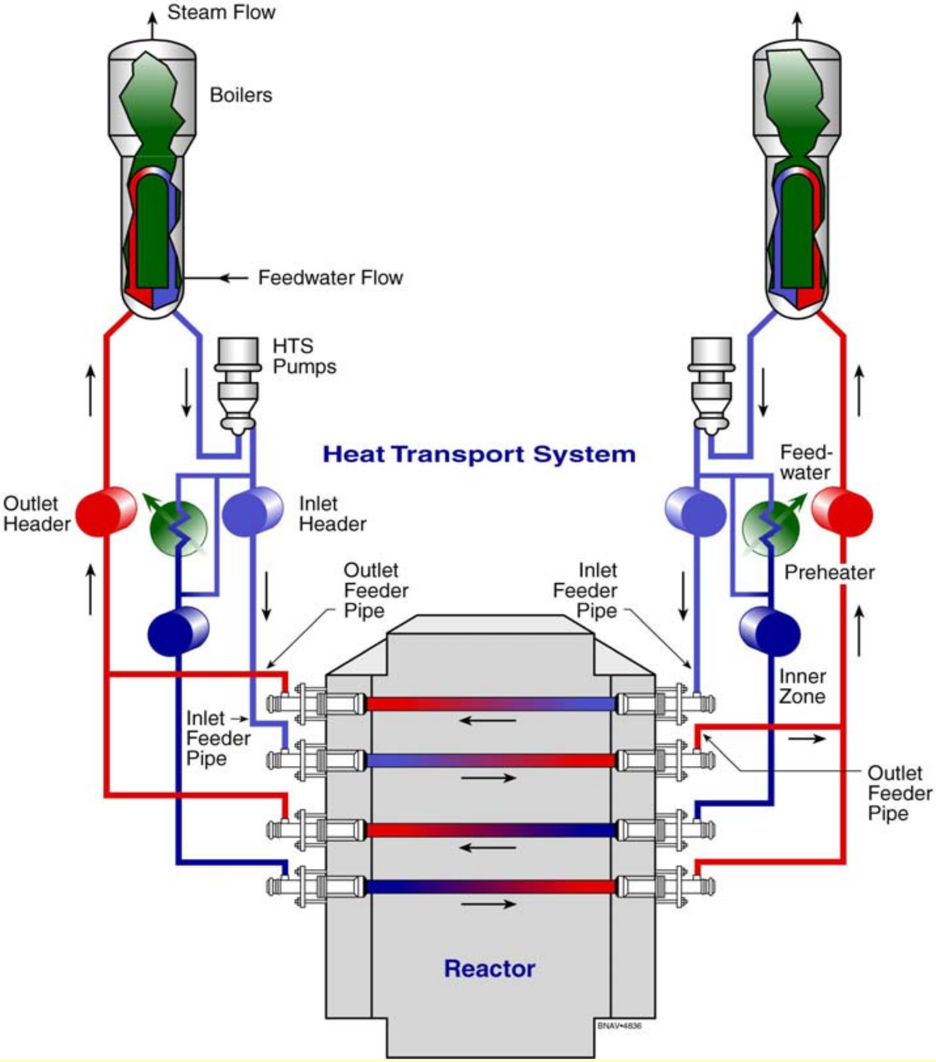
- Purification isolated during GSS
- Purification shutoff by operation of a shutdown system

HTS

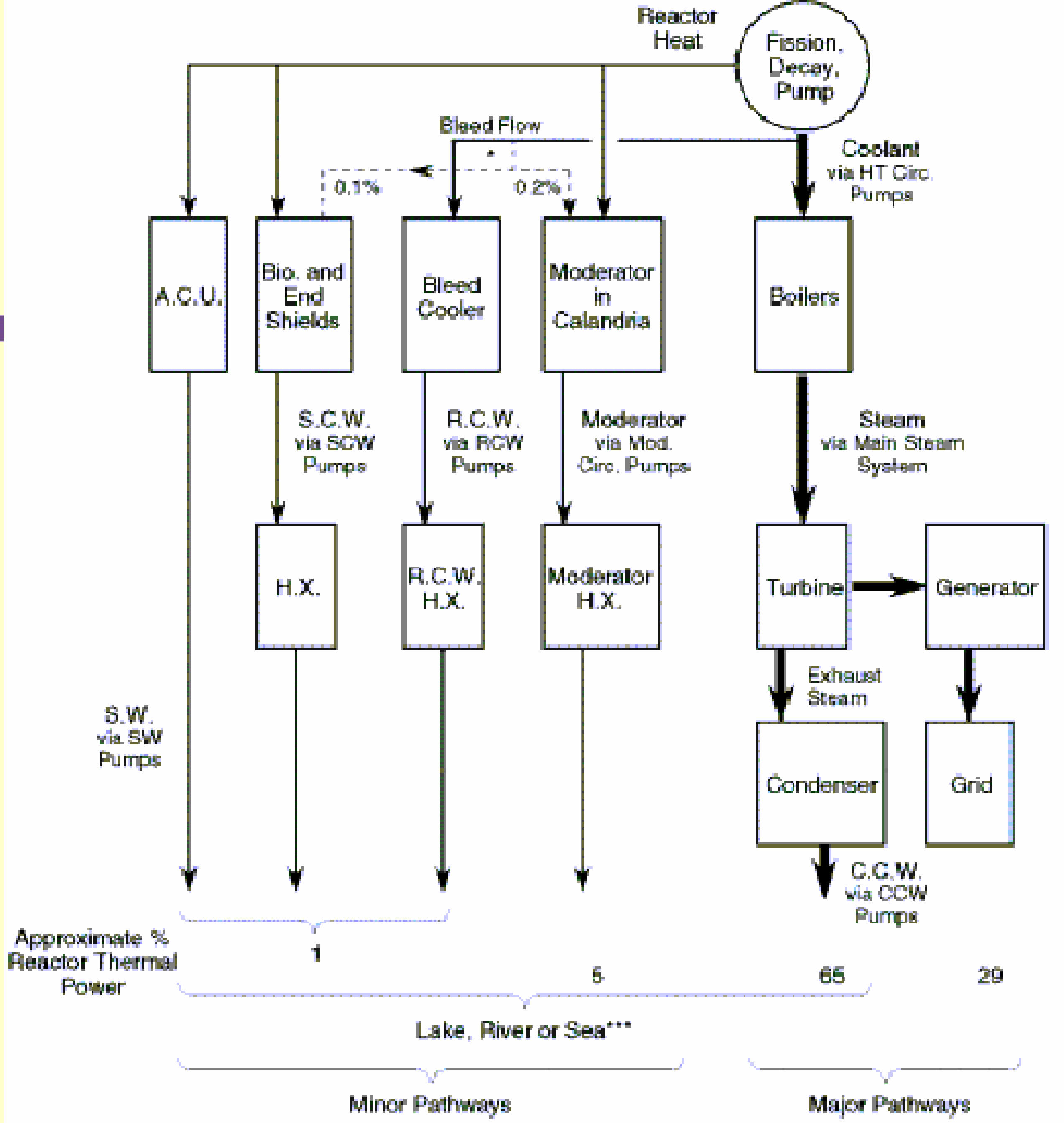




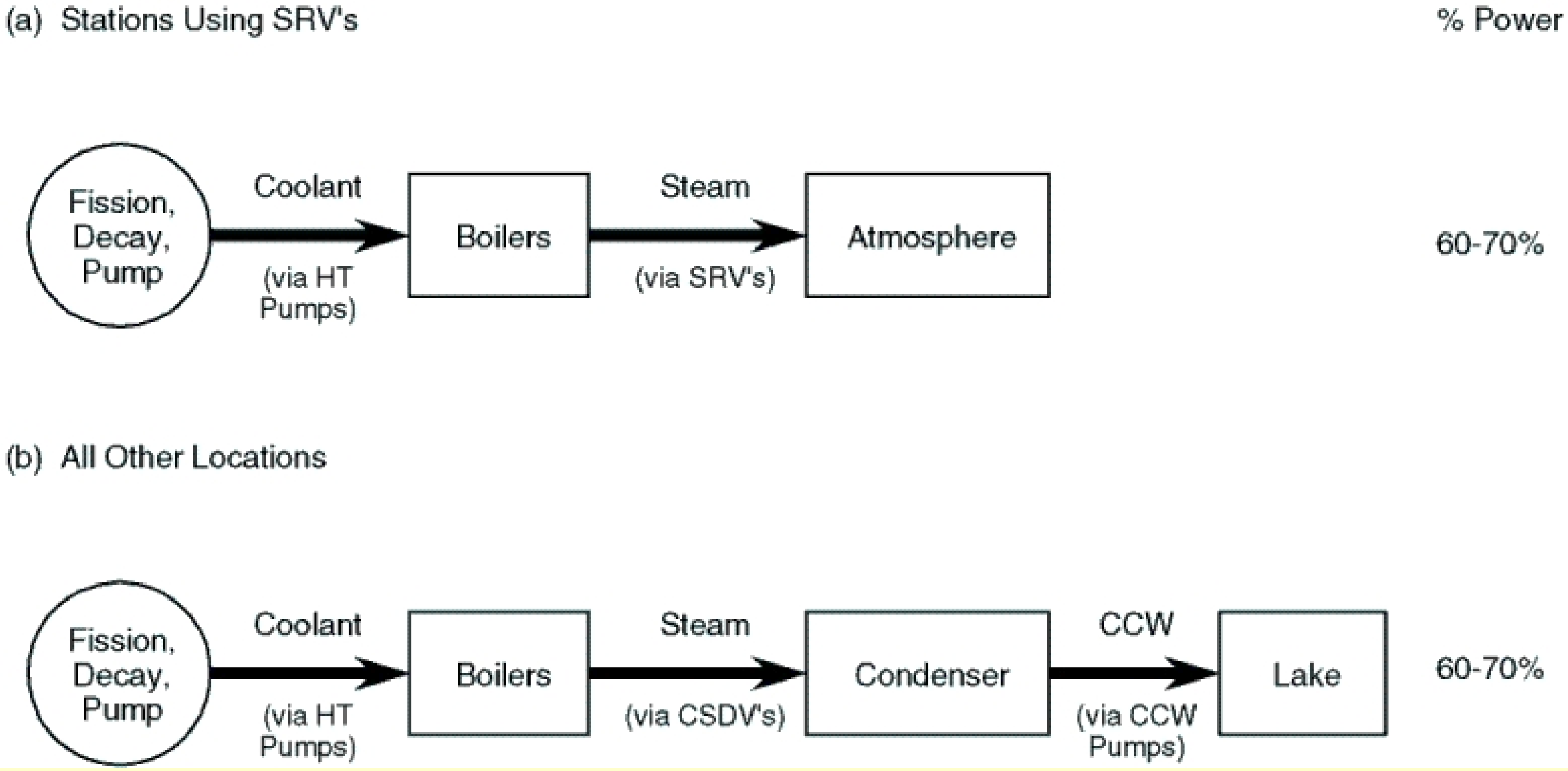
Pressure Control Stuff


Steam Flow
Boilers
Feedwater Flow
HTS
Pumps
Heat Transport System
Feed-
water
Outlet
Header
Inlet
Header
Preheater
Outlet
Feeder
Pipe
Inlet
Feeder
Pipe
Inner
Zone
Inlet
Feeder
Pipe
Outlet
Feeder
Pipe
Reactor
BNAV•4836

Full Power Heat Flow Paths



Poison Prevent



Radiological Hazards

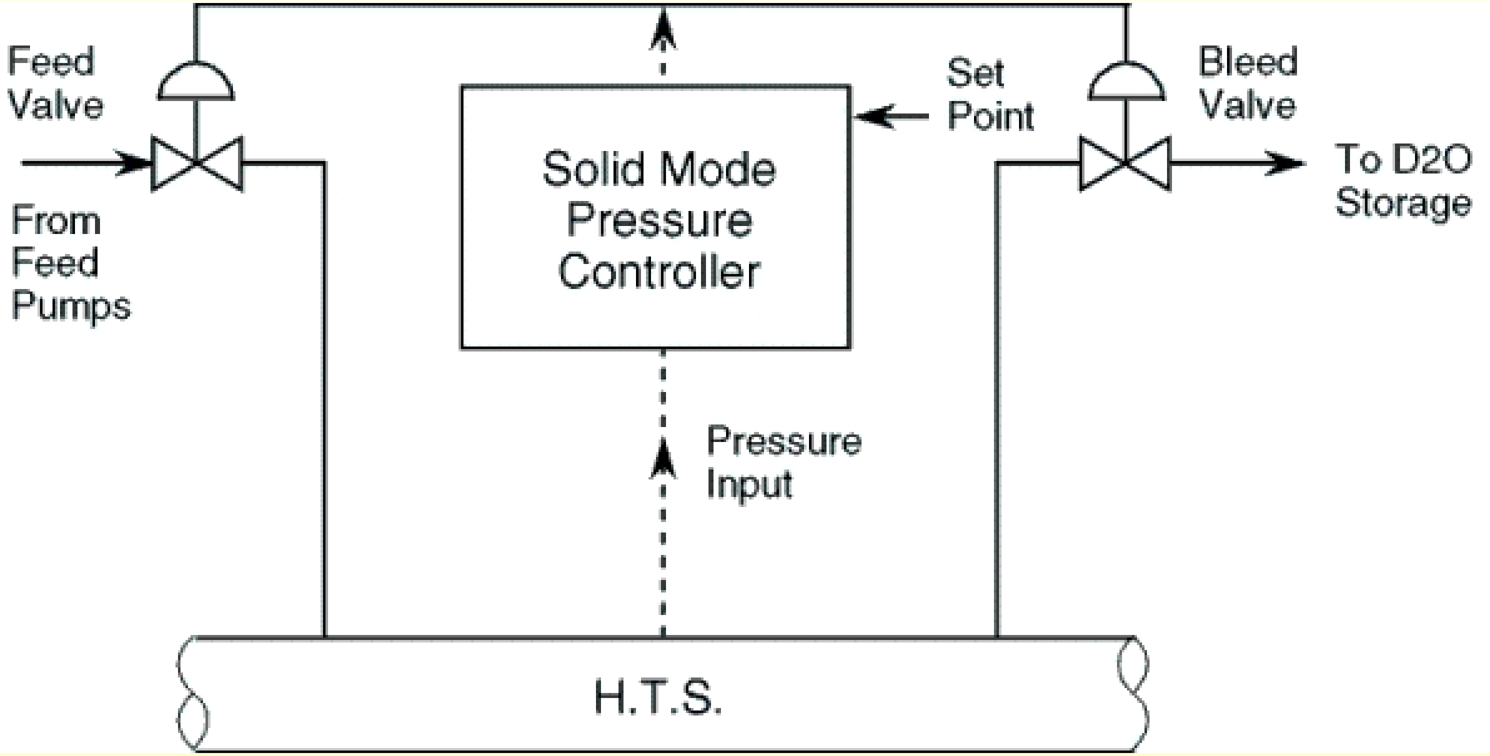
- N-16, O19 and Photoneutrons at power
  - Usually only in inaccessible areas.
- Contaminated water containing
  - Tritium
  - Fission Products
    - I-131
  - Activation Products
- Contaminated Surfaces
  - Plating out of activation products
  - Crud deposits
  - Collection in IX and filters

Hydrogen Addition

- Not enough
  - Excessive corrosion due to oxygen
- Too Much
  - Zirconium embrittlement
  - Hydrogen explosion hazard

Pressure & Inventory Control

Feed and Bleed



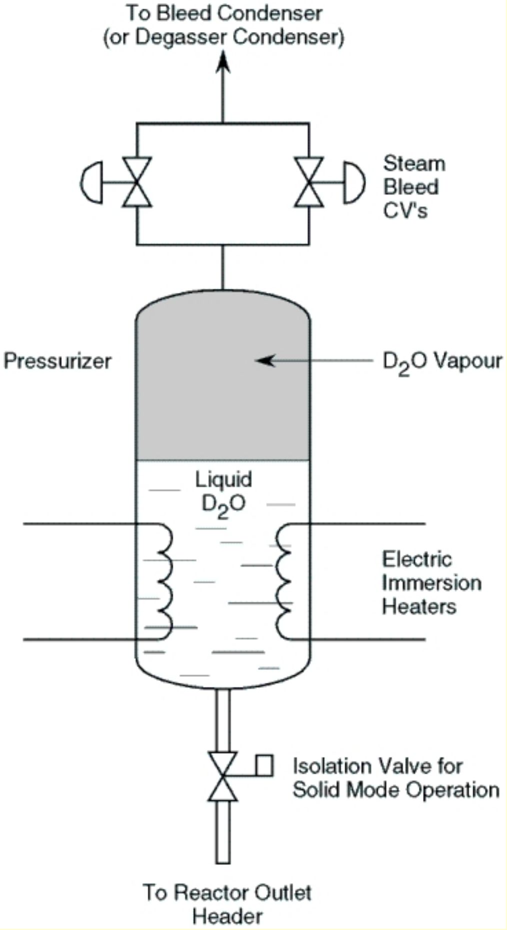
Feed and Bleed in Solid Mode

- Feed to increase pressure, bleed to reduce
- During warm-up bleed is open removing increased volume from system
- During cooldown feed is open
- Supplies D2O to gland
- Bleed condenser (degasser condenser) accepts coolant discharge

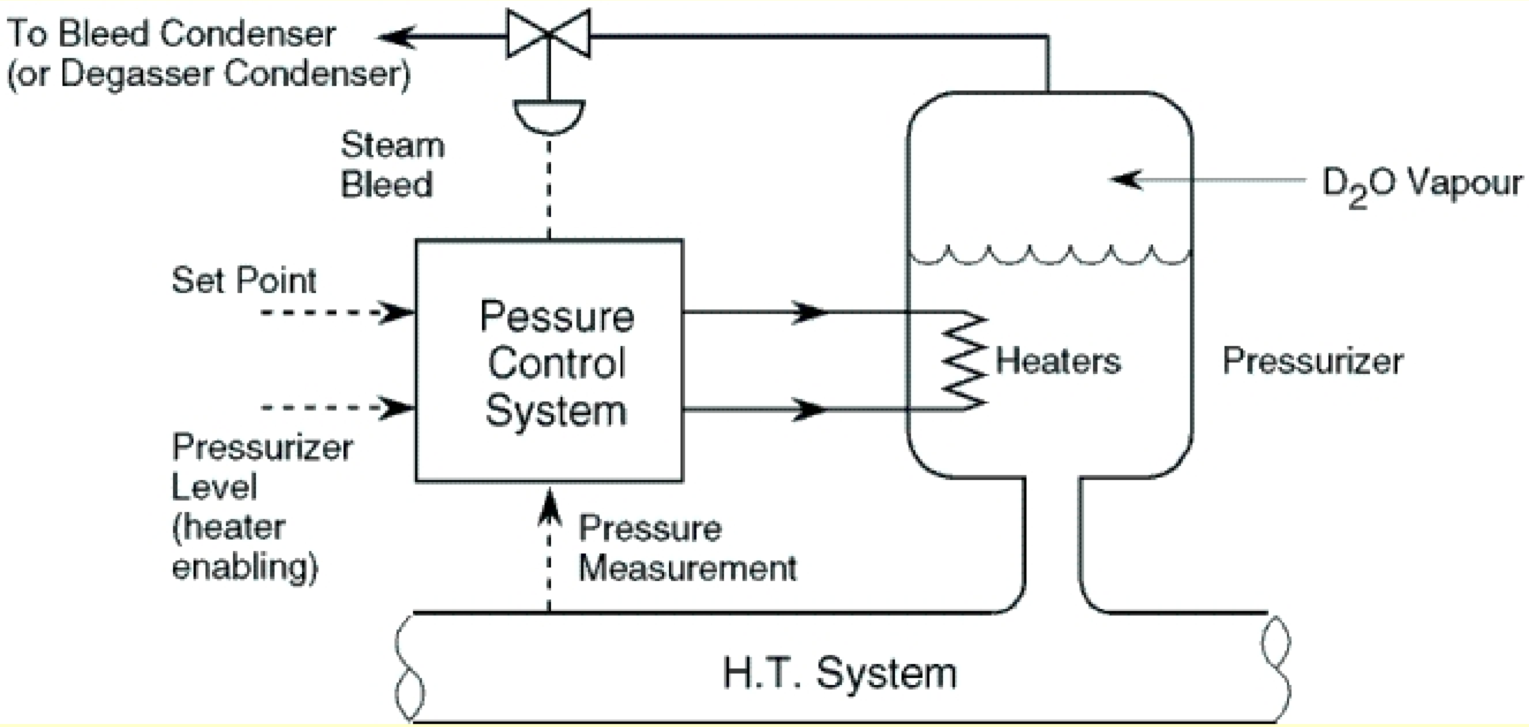
Feed and Bleed in Normal Mode

- Adjusts inventory to maintain correct level in the pressurizer
- Returns D_2O to the system to make up for losses
- Supplies water to purification
- Supplies gland seal system
- Bleed condenser accepts coolant removed from system

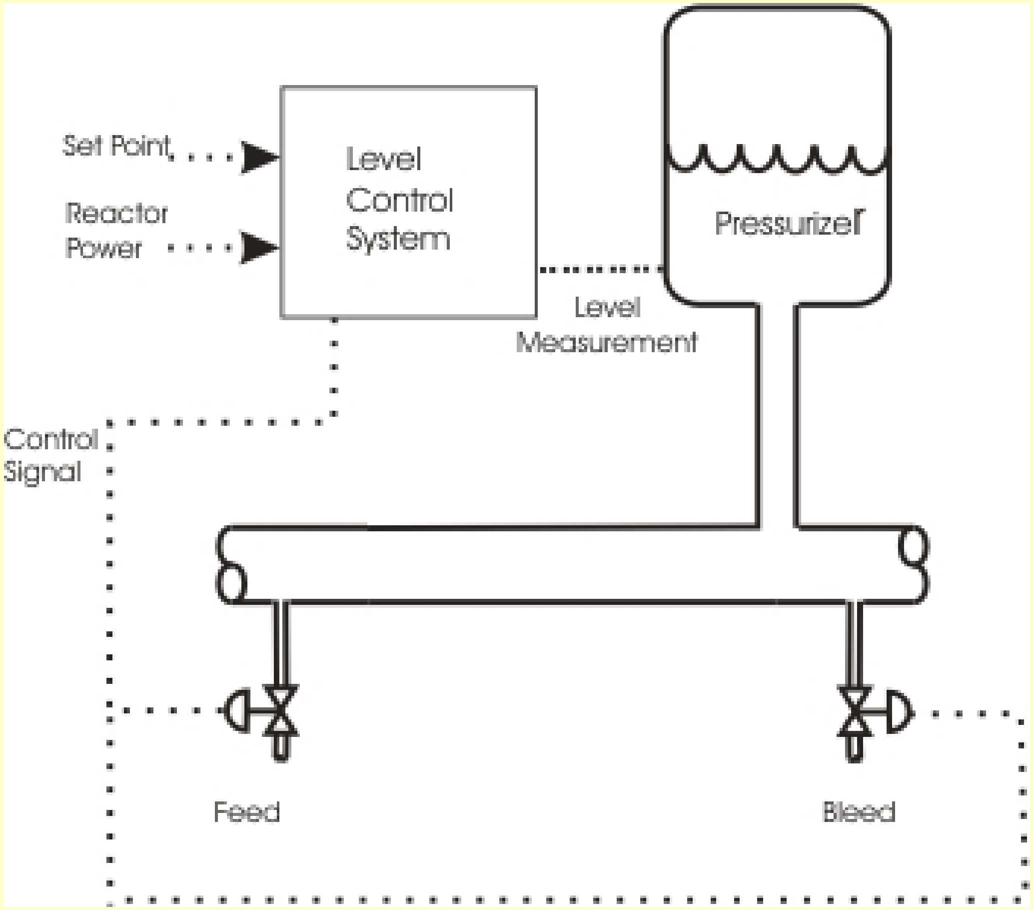
Typical Pressurizer



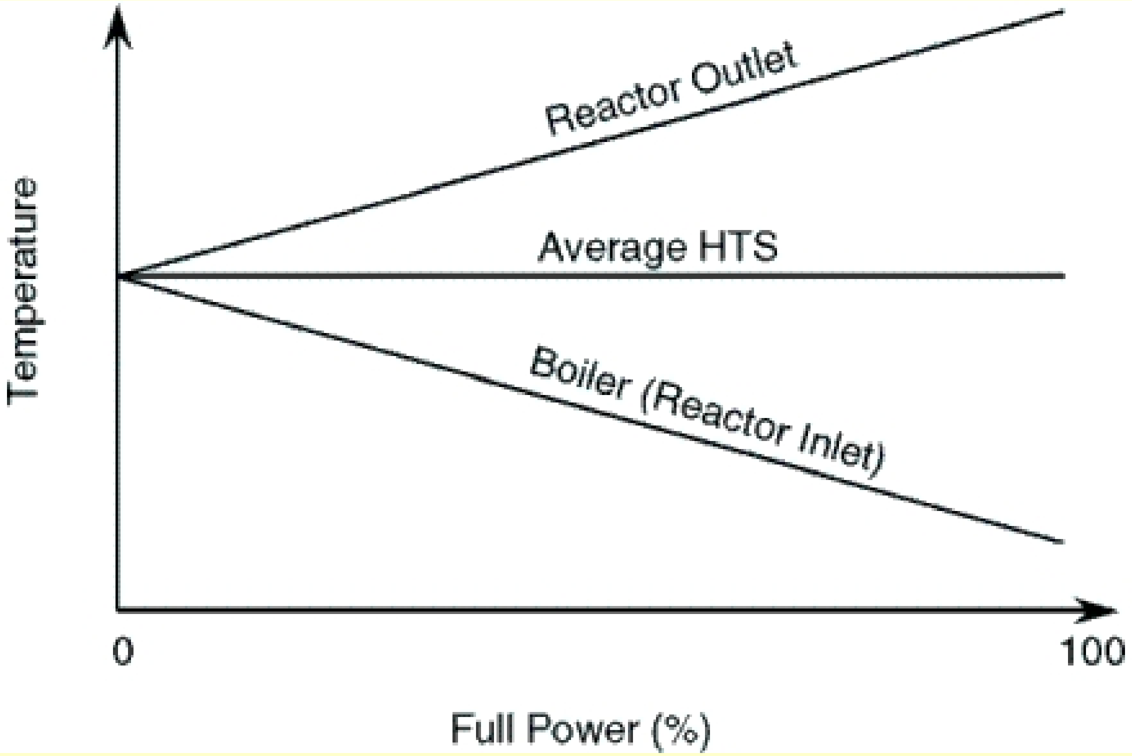
Pressure Control Using Pressurizer



Level Control of Pressurizer



Temperatures is a Feed and Bleed

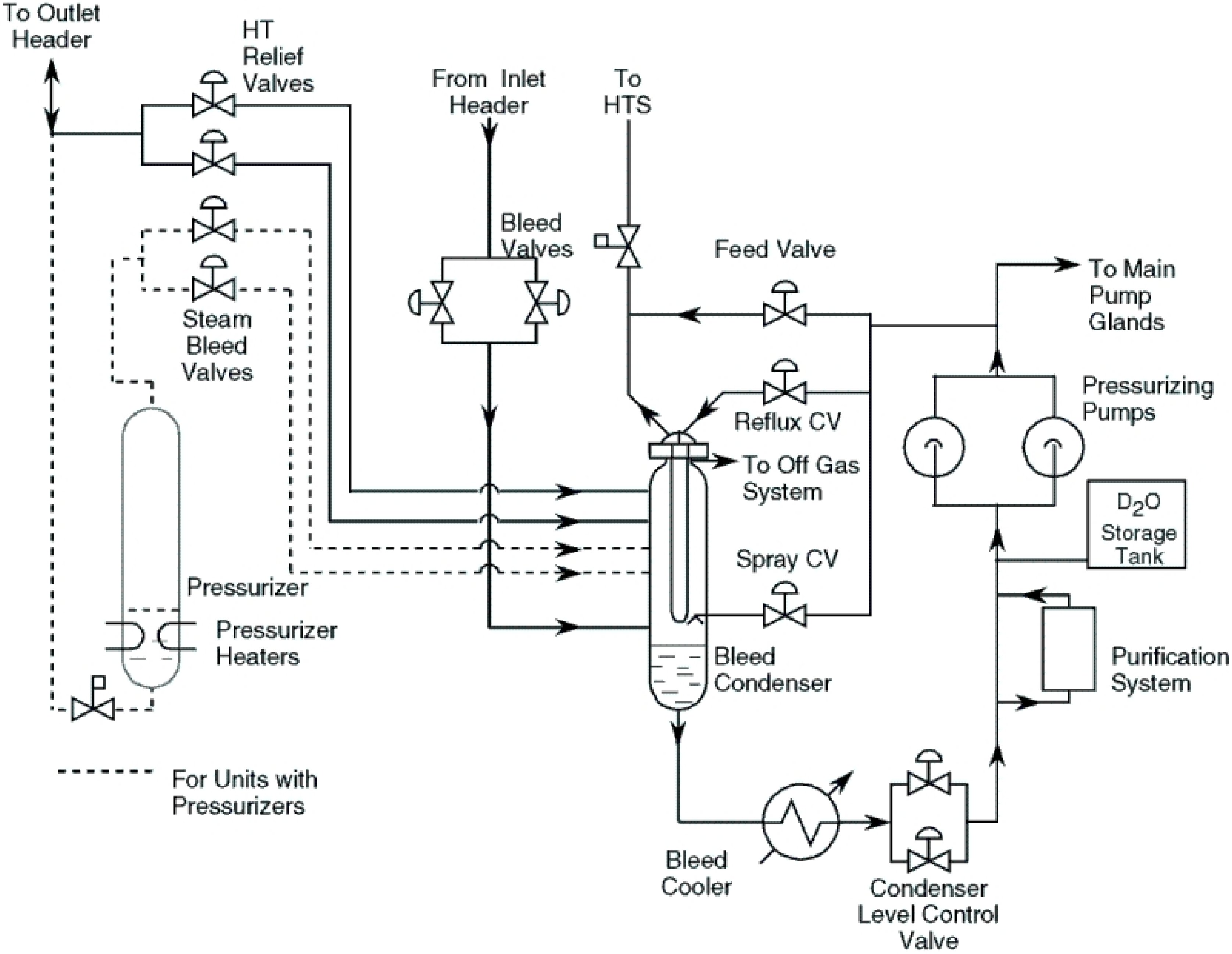


D_2O Transfer and Storage

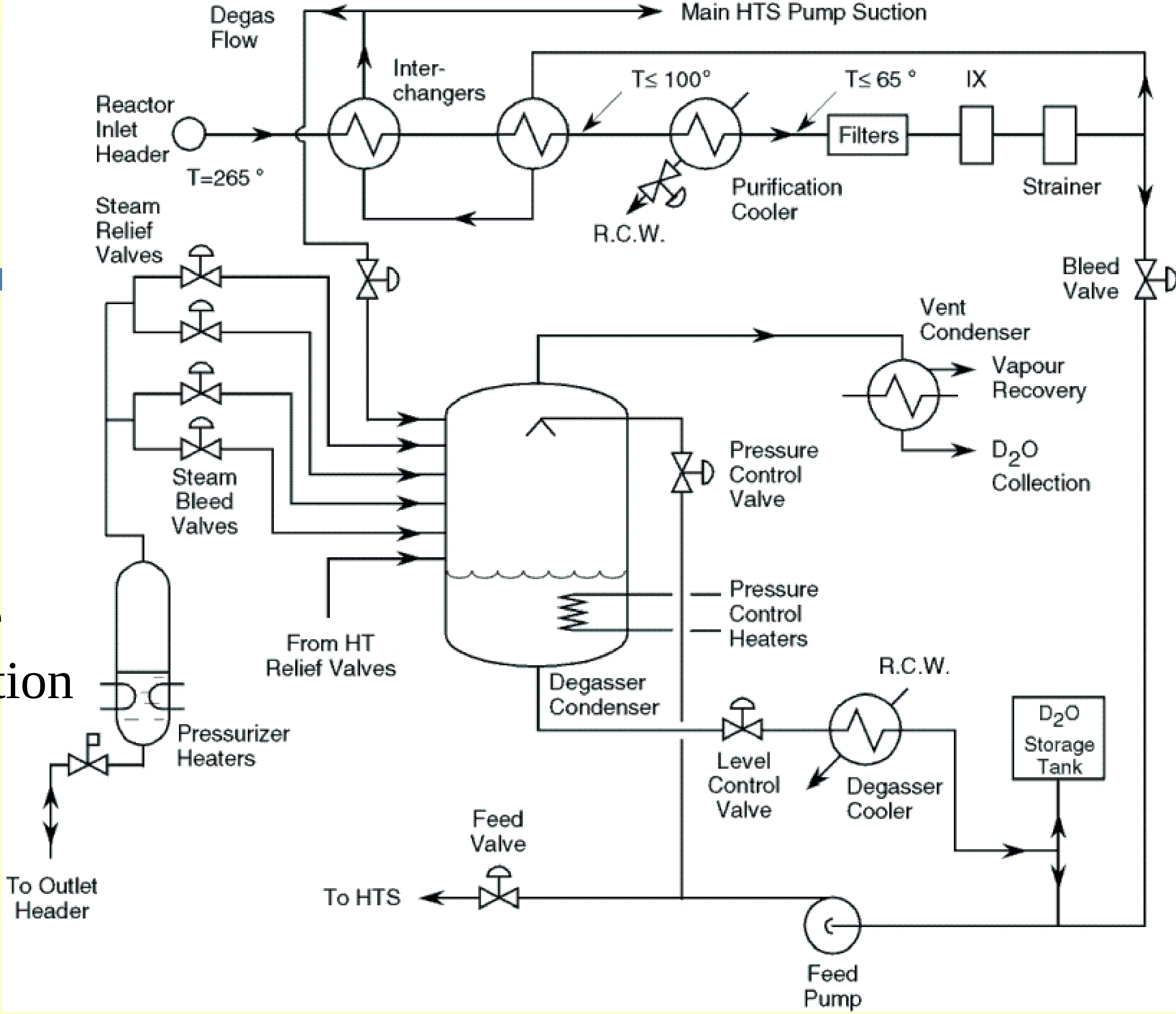
- In a multi unit station this is common to all units
- Water can be transferred from unit to unit
- Water can be transferred from a central storage area to or from any unit.

Unit D_2O Storage Tank

- Provide makeup for leakage
- Accommodate shrink and swell from power maneuvres
- Provide suction head for the feed pumps


To Outlet Header
HT Relief Valves
From Inlet Header
To HTS
Bleed Valves
Feed Valve
To Main Pump Glands
Steam Bleed Valves
Pressurizing Pumps
Reflux CV
To Off Gas System
D_2O Storage Tank
Spray CV
Pressurizer
Pressurizer Heaters
Bleed Condenser
Purification System
For Units with Pressurizers
Bleed Cooler
Condenser Level Control Valve

Full Pressure Purification



Pressure Relief

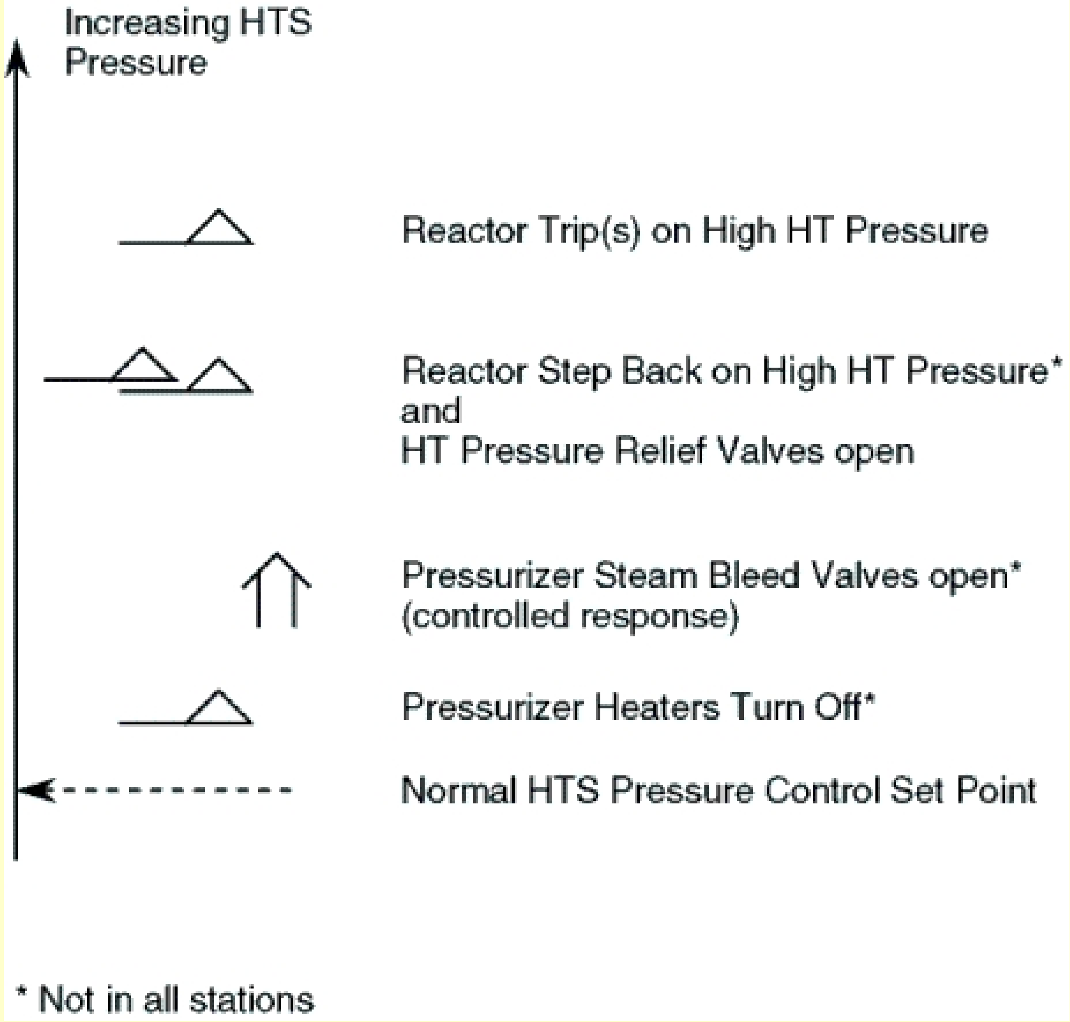
Potential Results

- Coolant spill requiring ECI
- Fuel failures because of decreased heat removal capacity
- Reactor power increase due to void reacivity

Overpressure Mechanisms

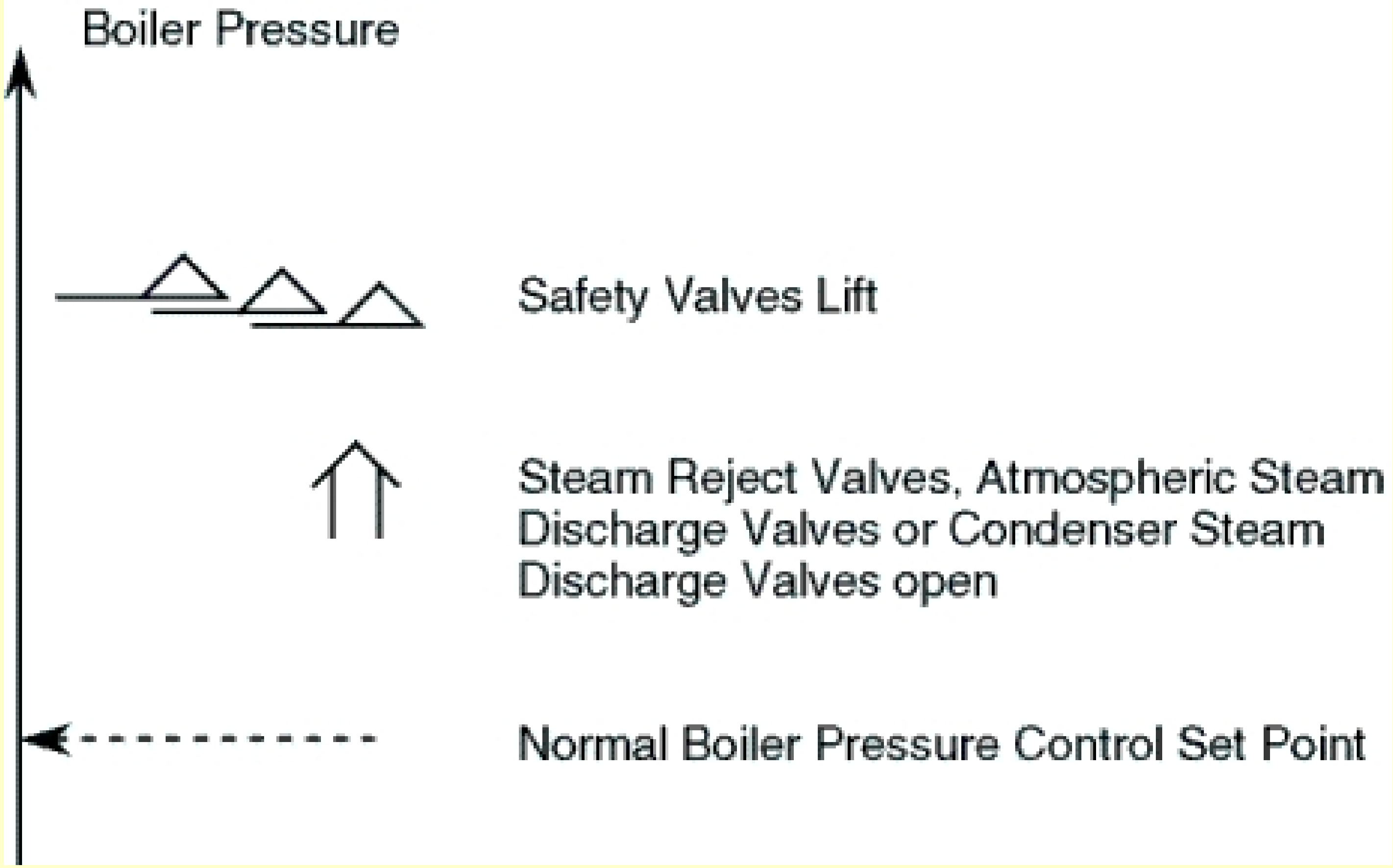
- Mechanical
  - Pumps supplying excess water
  - Bleed failure
- Swell due to increased temp
  - Pressurizer heaters failing on
  - Loss of regulation
  - Loss of HTS pumps at power
  - Loss of steam from boilers
  - Loss of feedwater to boilers

Direct Methods of Pressure Reduction



* Not in all stations

Indirect method of Pressure Reduction

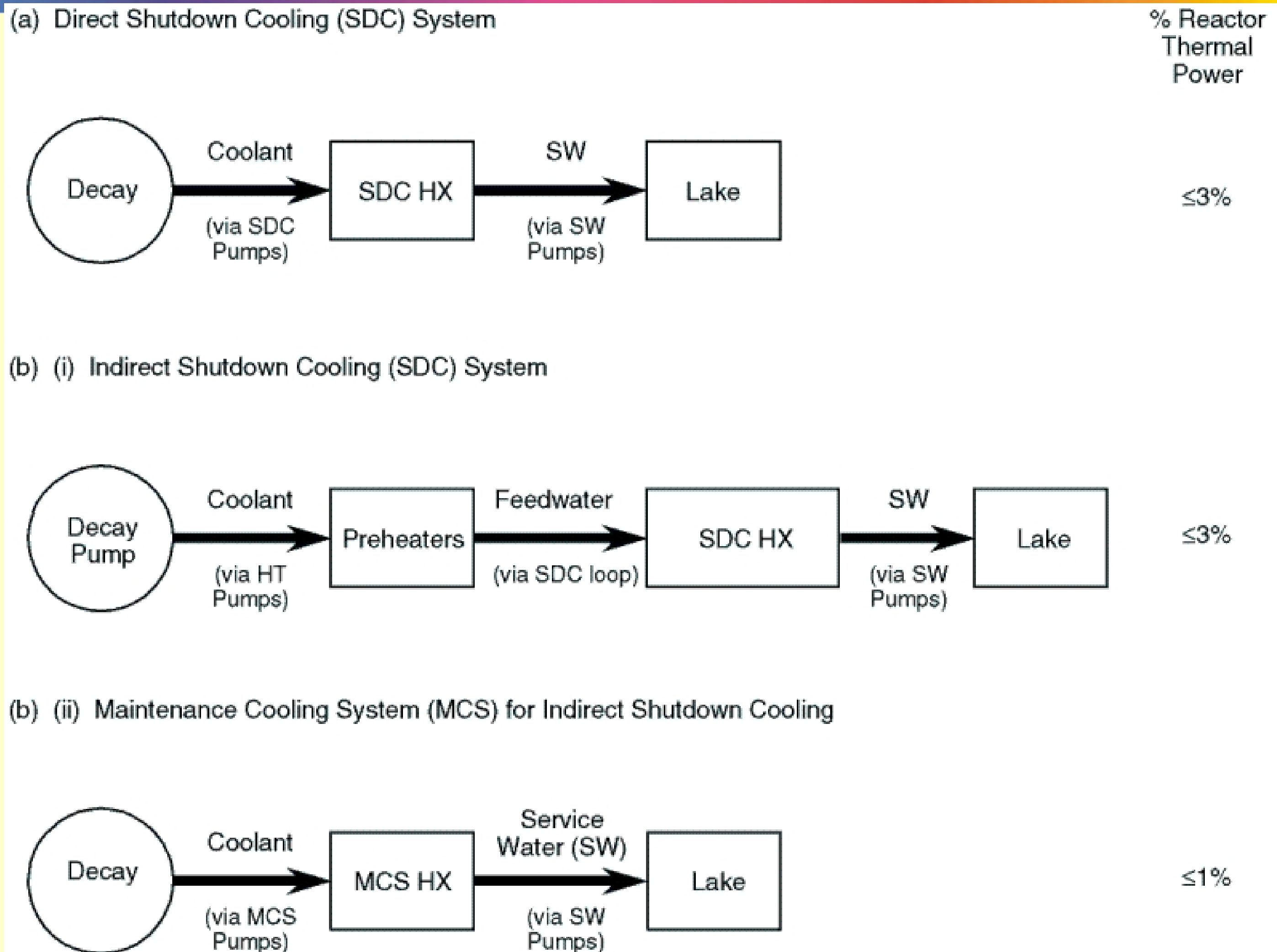


Upsets

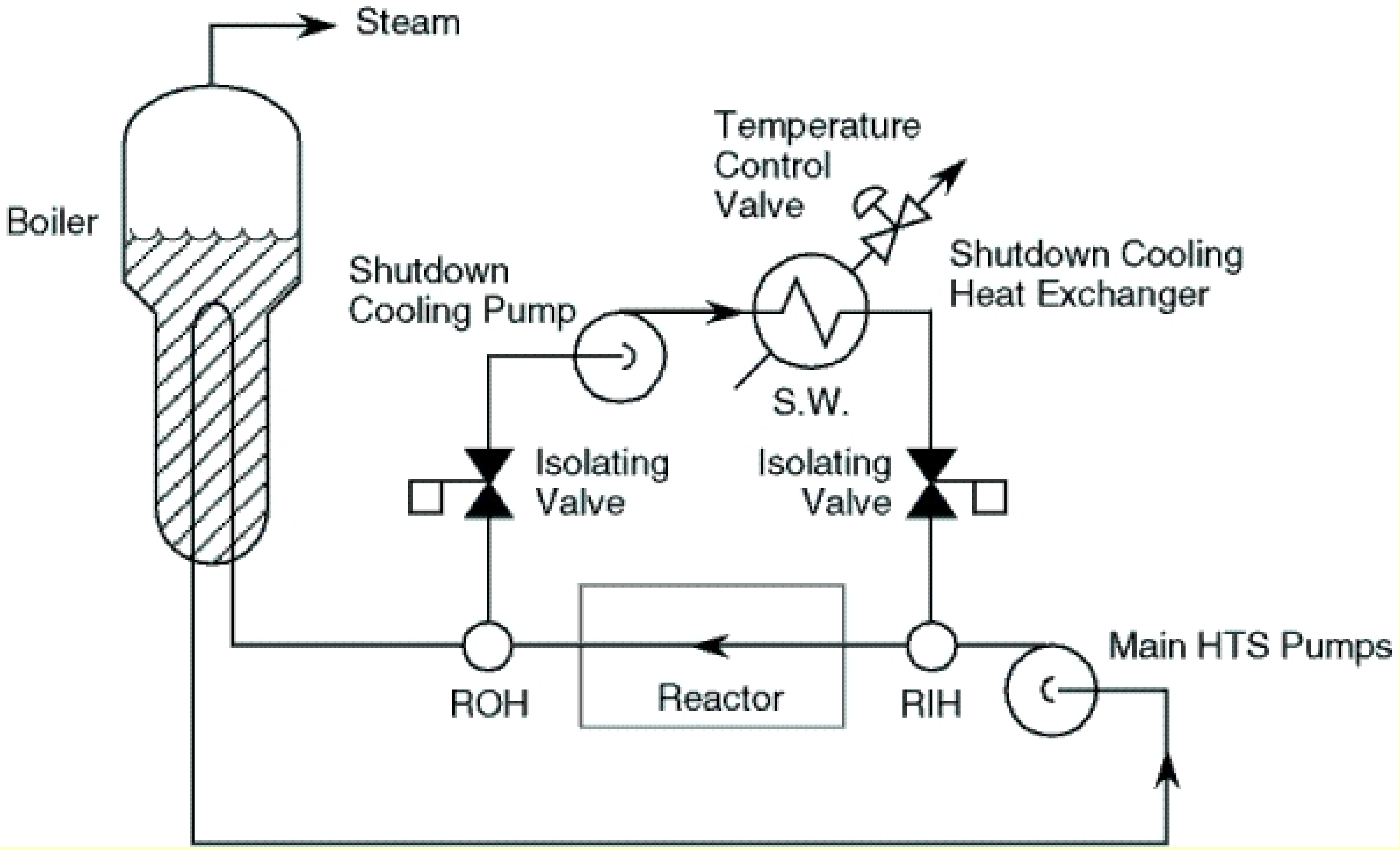
- Failed open PRV
- Feed pump failure
- Pressurizer steam bleed valve fails open
- Failure of HT pump
- Over ride of Bleed/Degasser Condenser Level Control

Shutdown Operation

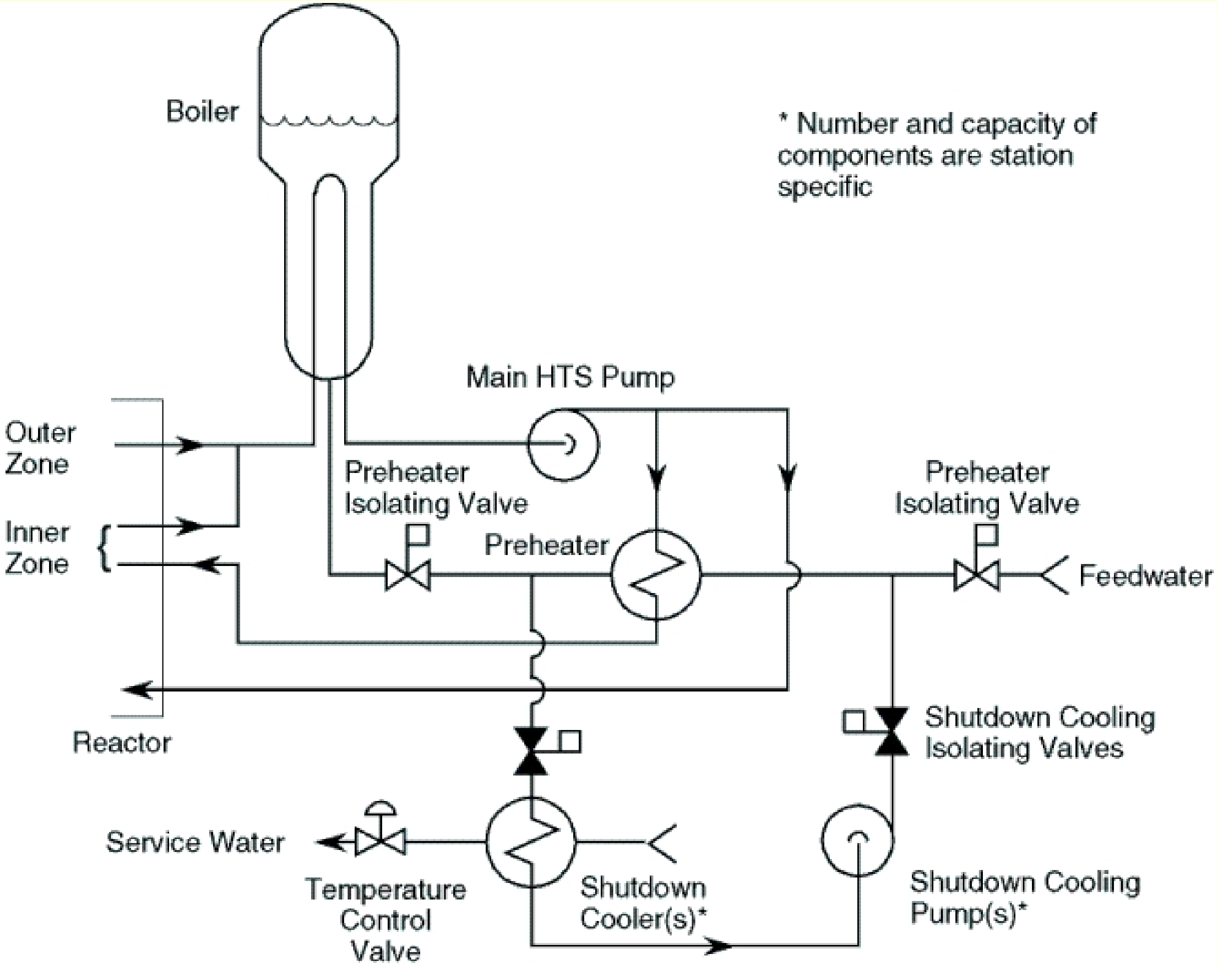
Shutdown Cooling Heat Paths



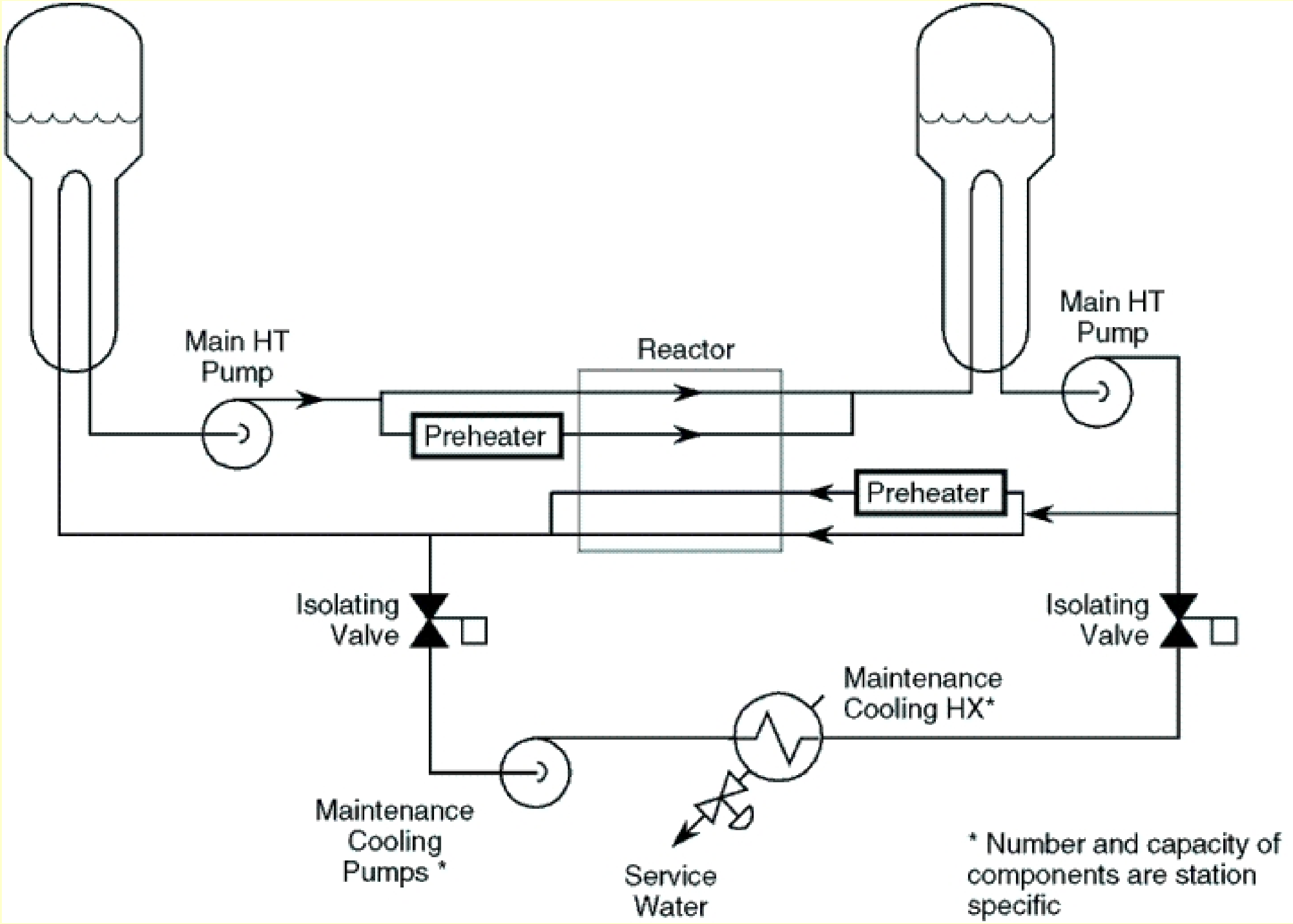
Direct Shutdown Cooling



Indirect Shutdown Cooling



Maintenance Cooling

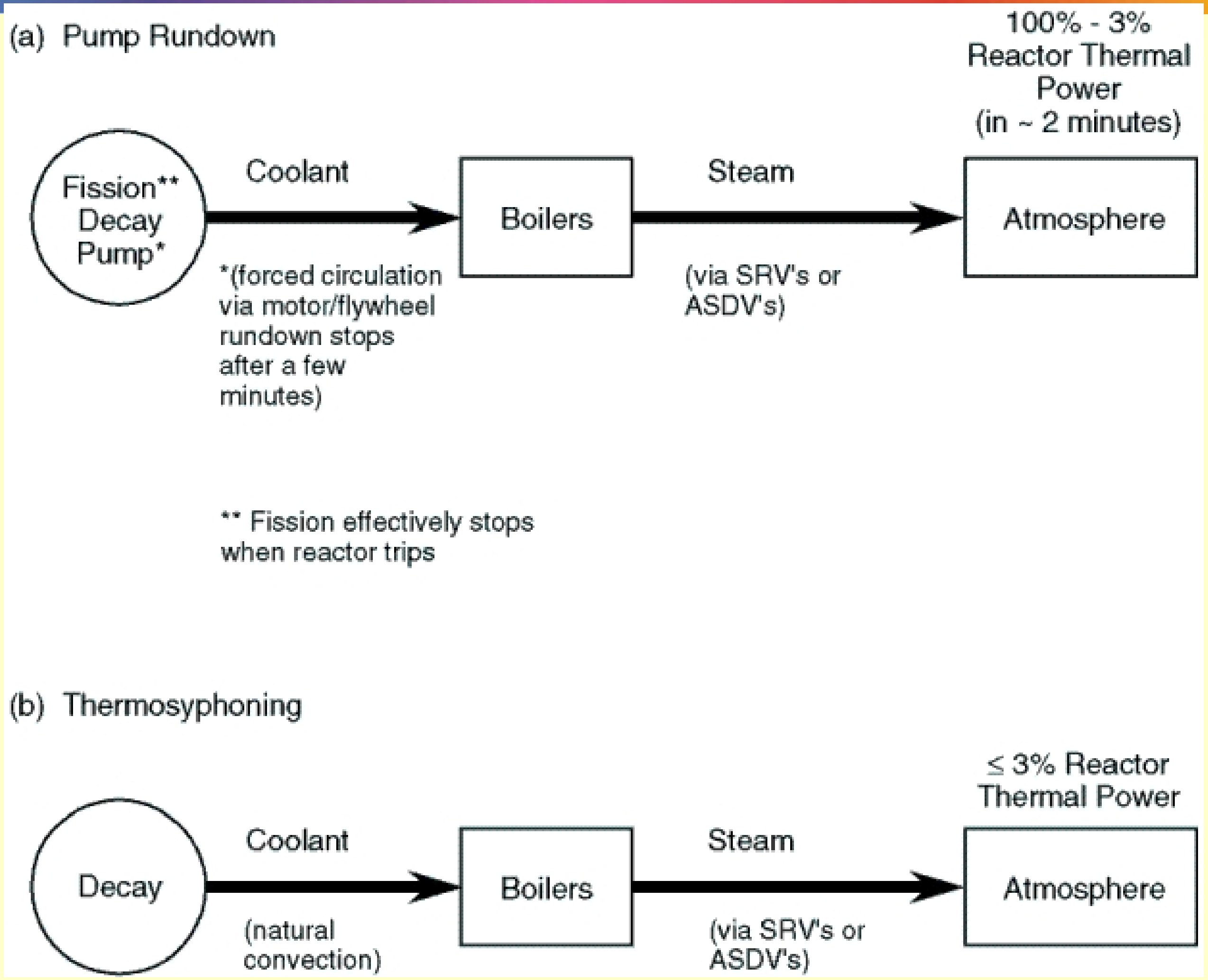


* Number and capacity of components are station specific

Abnormal Operation

- Shutdown cooling (direct and indirect)
  - Put into service at full temperature
  - Limited number of cycles
  - Would be done on excessive boiler tube leaks
- Maintenance cooling
  - Put into service at shutdown cooling temperatures
  - Limited number of times
  - Loss of class four

Loss of class 4



(a) Pump Rundown

*(forced circulation via motor/flywheel rundown stops after a few minutes)

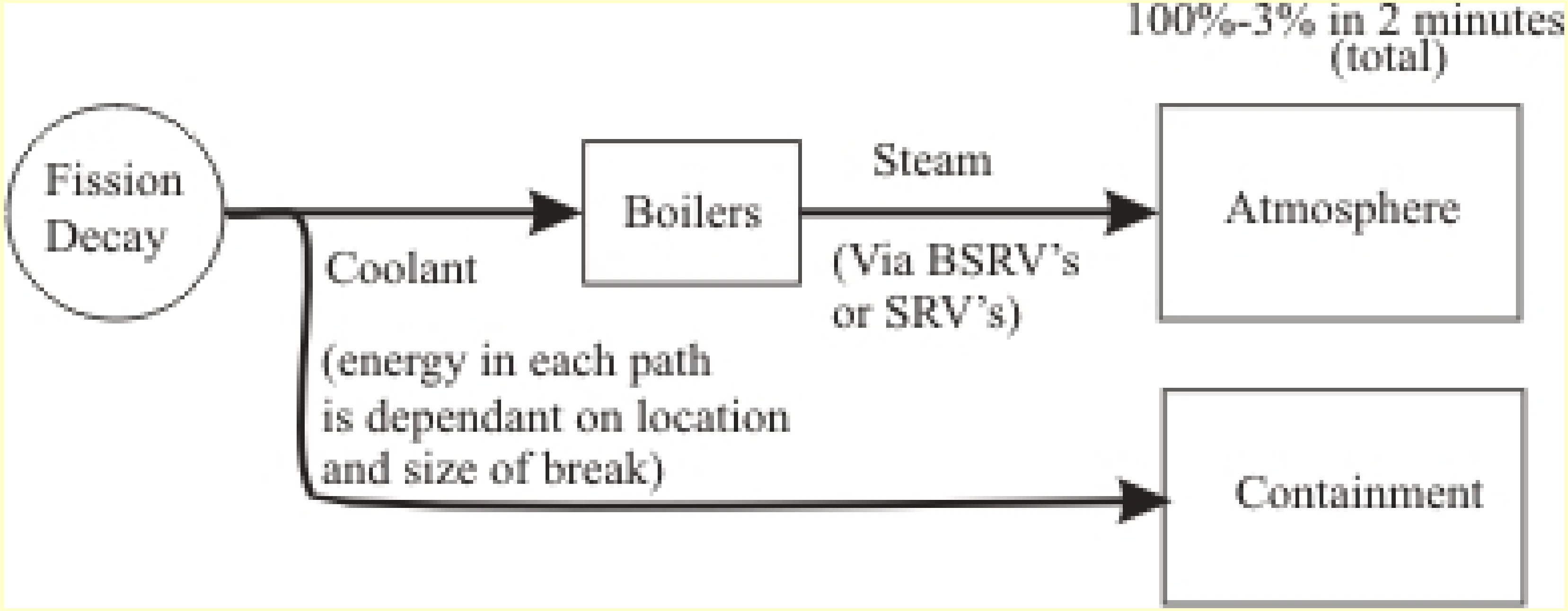
** Fission effectively stops when reactor trips

(b) Thermosyphoning

Conditions for Thermosyphoning

- Reactor power <3%
- Boiler pressure control operational
- Boiler heat sink available
- Pressure and inventory system operational

Crash Cooldown



HTS Water

Isotopic Limits

- High
  - Minimize positive reactivity insertion in the event of an in-core LOCA
  - Dependent on the moderator isotopic and perhaps poison load
- Low
  - Minimize the reactivity pulse on a LOCA
  - Economic

Downgrading of HTS

- Accidental addition from makeup or collection
- Improperly deuterized IX resins
- H2 addition
- In leakage to collection

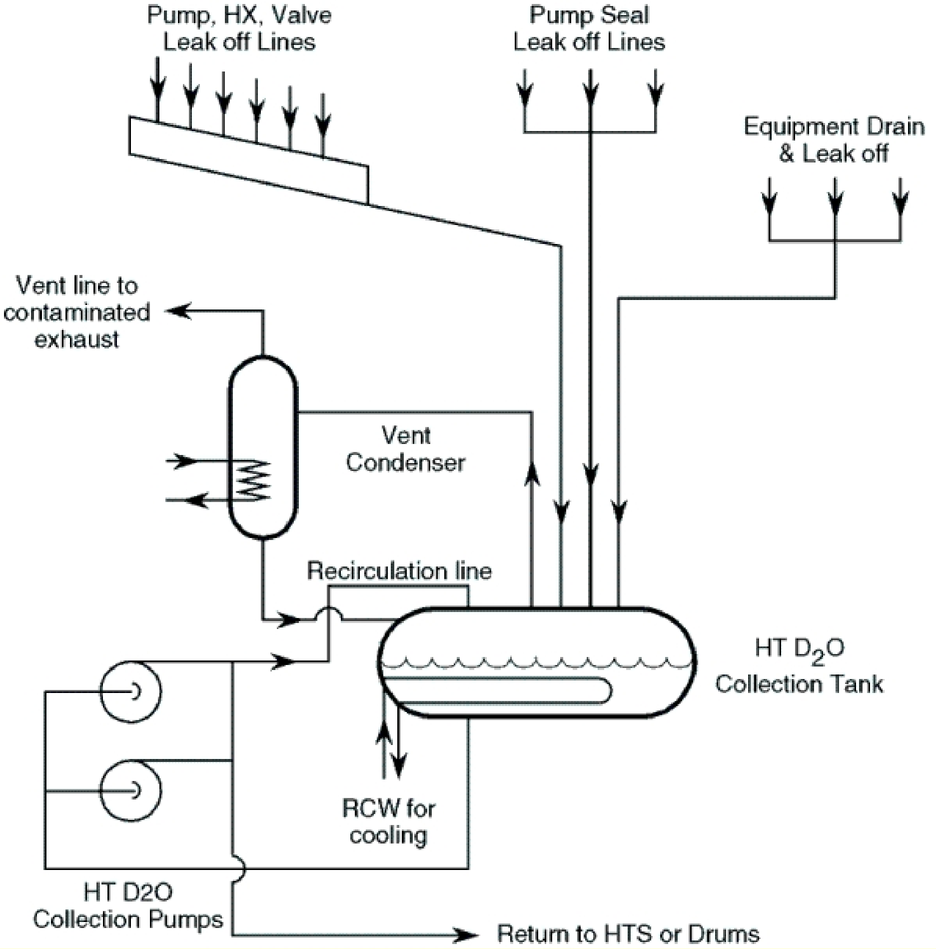
Effects of Downgrading

- Slow additions
  - No observable effect
  - Increased fueling
  - Found by sampling
- Sudden downgrading
  - Zones drop
  - Adjusters might drive
  - Increased fueling
  - Shutdown if downgrading takes isotopic below limit

Collection

- D_2O Collection
  - Main pump seals, bleed cooler vents and drains, HTS vents, HTS valve glands
- Miscellaneous D_2O collection
  - Collection from points likely downgraded

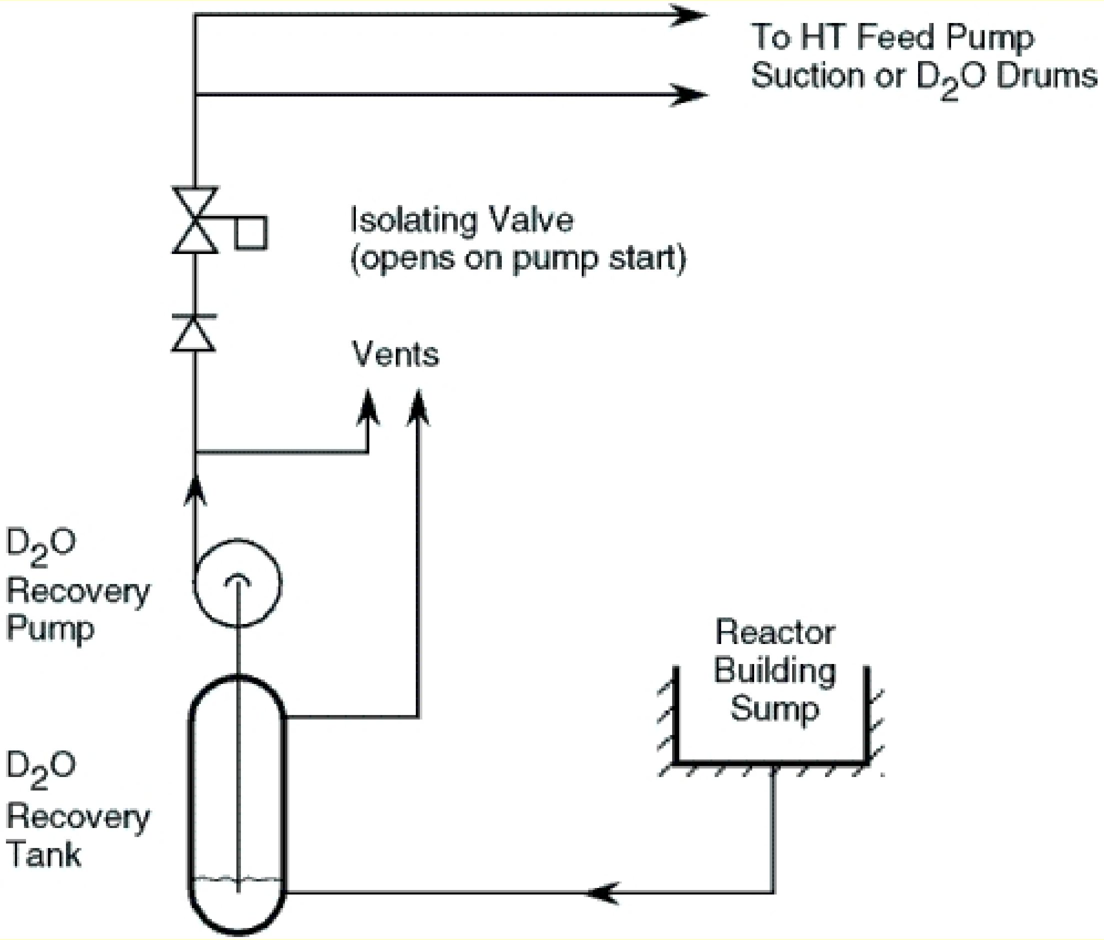
D_2O Collection System



Recovery

- Vapour Recovery
  - Recovers D_2O
  - Detects chronic small leaks
  - Reduces tritium
  - Reduces containment pressure
- Liquid Recovery System
  - Collects water from system
  - Can be used and prevent ECI is some situations
    - Prevents shutdown of other units
    - Prevents thermal stress

Recovery System

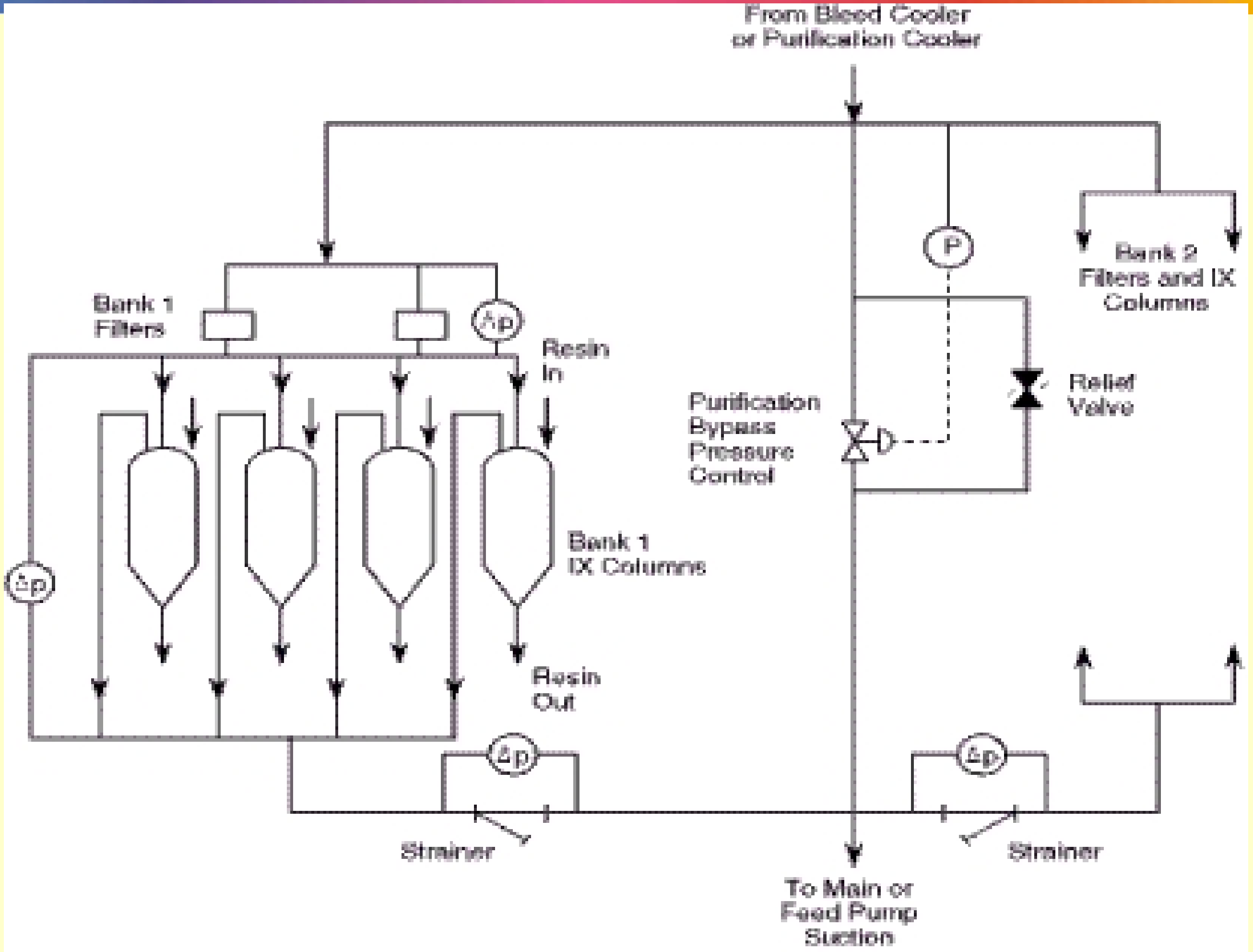


Other Leakage Indications

- Pressure tubes
  - High dew point in annulus gas
- Boiler Tubes
  - D_2O in H_2O
  - Potential to release radioactivity from unmonitored routes
  - D_2O is non recoverable

Purification

Purification System



Important Parameters

- Flow
  - Typical 8-10kg/sec
  - Set to maintain chemistry
  - Maximum about 40 kg/sec (25kG/sec in full pressure purification
  - Flow set higher to remove fission products or crud from a crud burst
- Temp
  - Ion exchange efficiency
  - IX bead melting
  - Release of chemicals

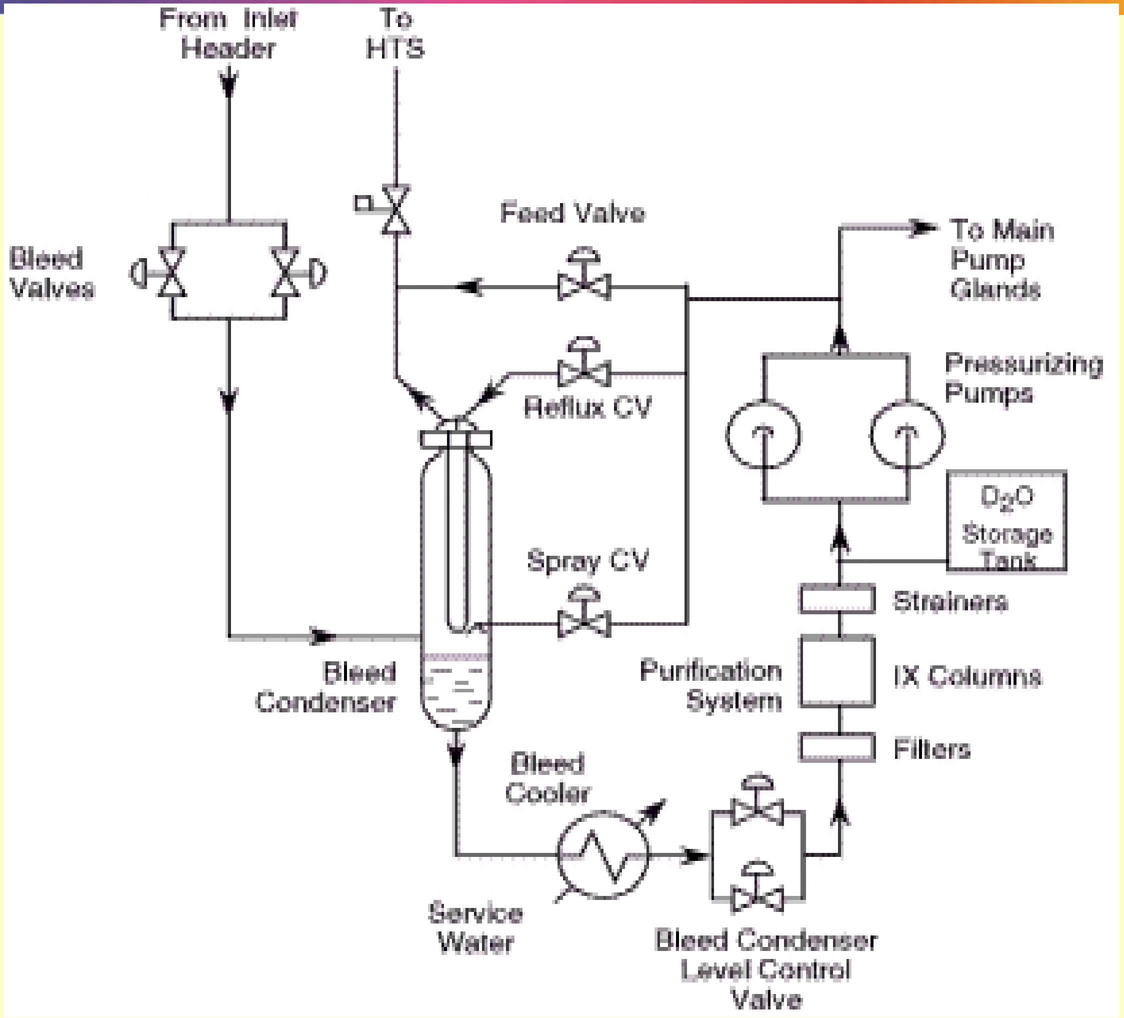
More Important Parameters

- ΔP
  - High ΔP limits flow
  - Show need to clean strainers
  - Replace filters
  - Solid impurities in columns
- Inlet Pressure
  - Too high increases flow and reduces efficiency
  - Bypassing purification
  - Operating relief valves

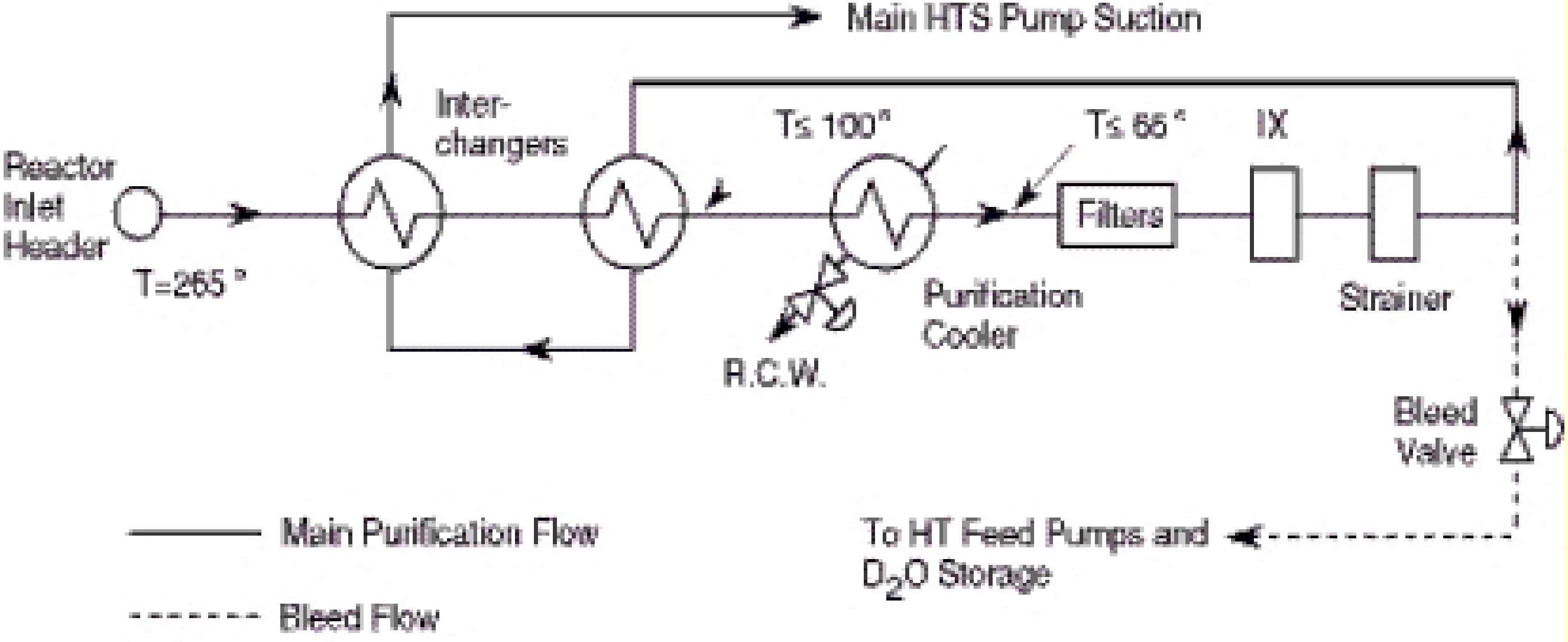
Abnormal Conditions

- I-131 removal
  - Failed fuel releases I
  - License limit on I-131
- Crud removal
  - Crud bursts when system has chemical or thermal shock
  - Typically during power maneuvres

Reduced Pressure Purification



Full Pressure Purification

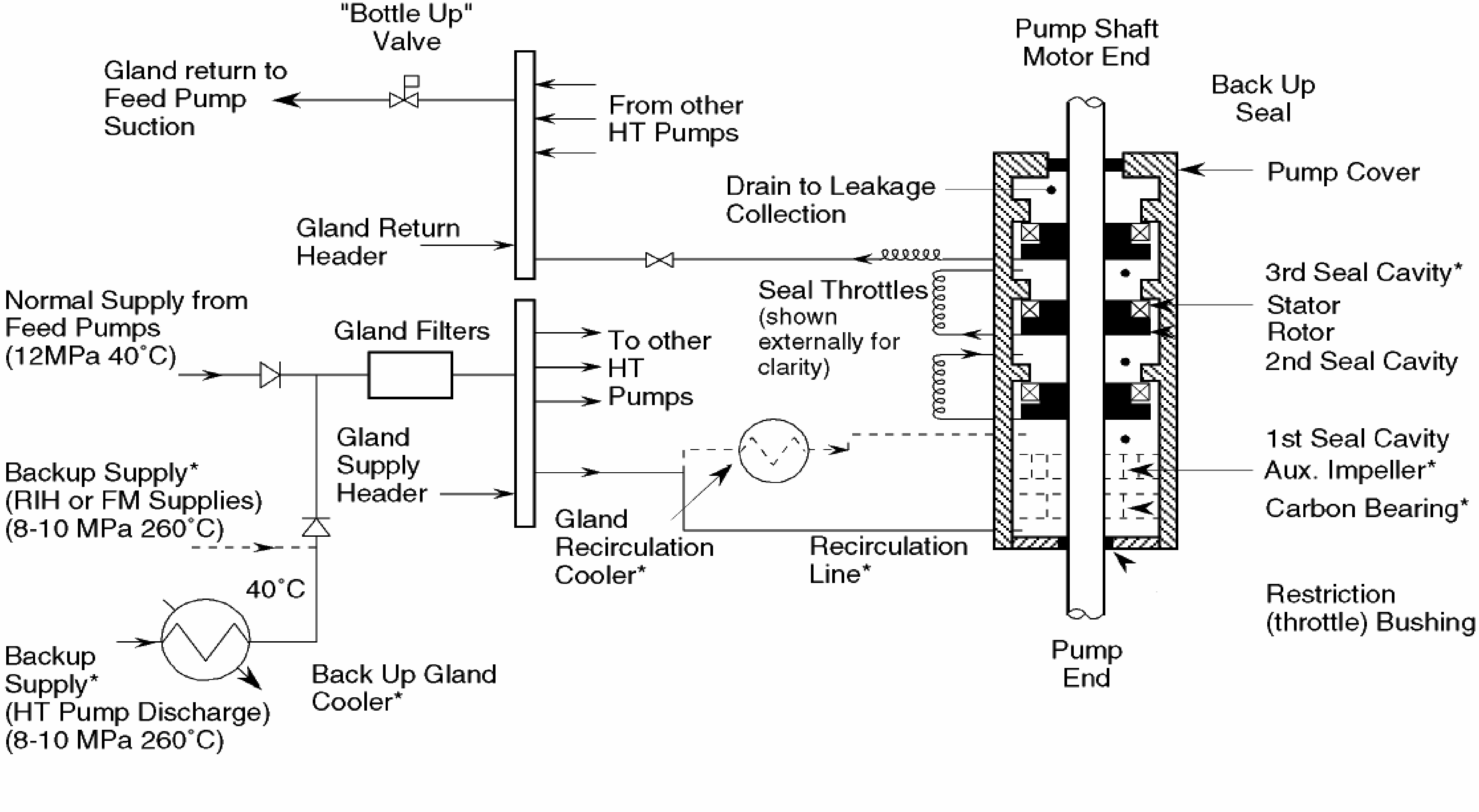


Hydrogen Addition

- Added to scavenge oxygen
- Presents an explosion hazard where it comes out of solution
  - Bleed condenser, D_2O storage tank
- Off gassing circuit removes gas from these locations

Tube Blanketing

Gland Seal Supply



* Only in some stations

\- - - Used only if pump bearing is part of gland

Special Safety Systems

Shutdown Systems

Shutdown Systems

- Independent
  - From each other
  - RRS
  - Any process system
- Interlocks
  - Fill zones
  - Drop control absorbers
  - Lower reactor power set point
  - Shutoff purification

Trips

- Absolute and conditional
- Redundant parameters
- Staggered trip set points
- Local and general coincidence

Typical Parameters

- High neutron power
- Neutronic rate
- HTS pressure high
- HTS pressure low
- HTS gross low flow
- Pressurizer low level
- Boiler level low
- Feedwater low pressure
- Moderator temp high
- RB high pressure
- HT high temp

ECI

Initiation

- 2 out of 3 or 3 out of 4 logic
- Primary and one conditioning parameter
  - Low HTS pressure
  - Vault high temp, vault/RB high pressure, high moderator level, low HT flow, sustained low pressure

ECI Phases

- Blowdown
- Injection
  - Sometime injection has two phases
- Recovery

Blowdown

- The time period it takes to depressurize
- Faster pressure gets down the faster cooling is restored
- Initial depressurization due to leak
- Drop due to shrink when the reactor trips
- Crash cooldown
  - Get injection quicker
  - Reduce leak rate
  - Remove boilers as a heat source

HTS Circulation

- Pumps left running as long as possible
  - Use boilers as heat sink for as long as possible
  - Mix vapour and coolant
- Main pumps may cavitate
  - Seals will eventually fail
- Pump inertia and thermosyphoning provide circulation after pumps trip
- Low speed drives in some stations

Injection

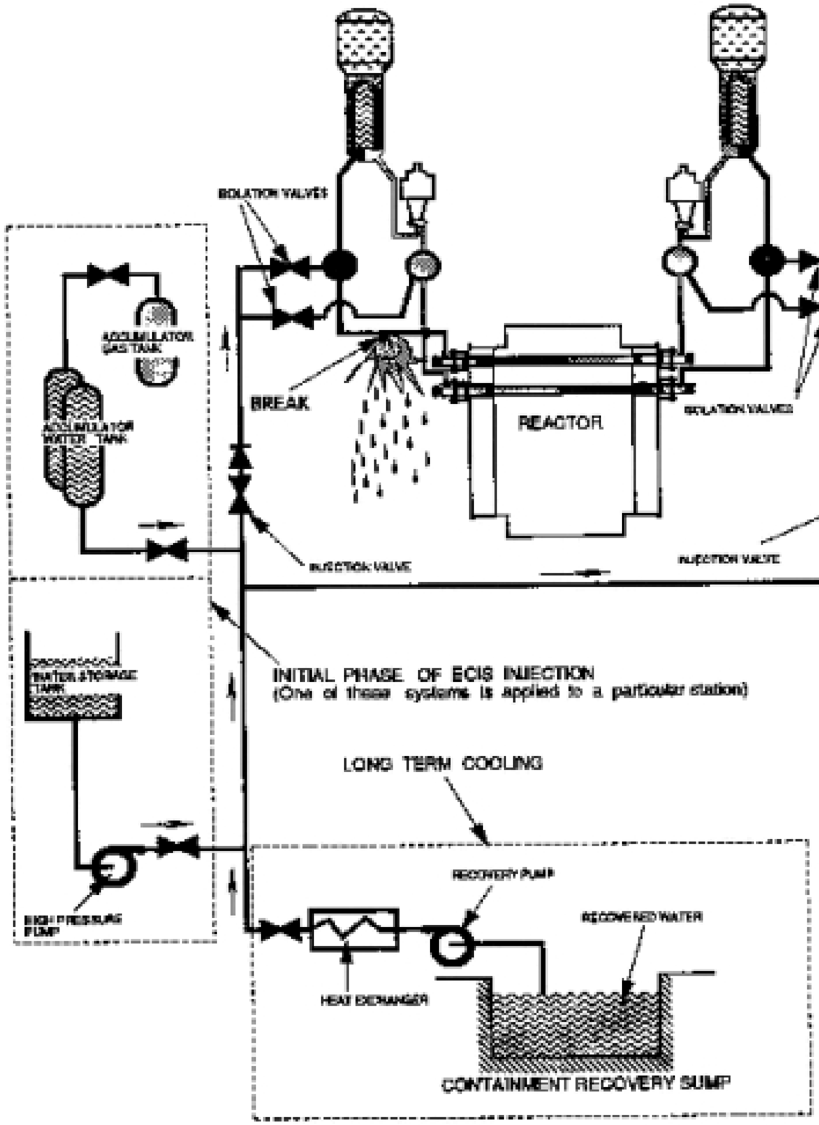
- Light water from storage tanks
- High pressure pumps <u>or</u> N_2 gas
- Some places use low pressure injection following high pressure

Injection Initiation

- Initiation pressure 4.2 to 5.5 MPa
  - Cost of equipment
  - Reduce the time that the system will be pressurized with ECI blocked
  - Reduce water hammer

Recovery

- Sometimes referred to as post accident water cooling
- Water is taken from a sump and pumped back through the reactor
- Screens in pumps to filter debris
- May drastically alter radiation fields in plant


ISOLATION VALVES
ACCUMULATOR GAS TANK
ACCUMULATOR WATER TANK
BREAK
REACTOR
ISOLATION VALVES
INJECTION VALVE
INJECTION VALVE
WATER STORAGE TANK
HIGH PRESSURE PUMP
INITIAL PHASE OF ECIS INJECTION
(One of these systems is applied to a particular station)
LONG TERM COOLING
RECOVERY PUMP
RECOVERED WATER
HEAT EXCHANGER
CONTAINMENT RECOVERY SUMP

Operating States

- Poised
  - Must be here to run normally
- Blocked
  - Automatic initiation is prohibited
  - Normal when HTS is depressurized
- Recallable
- Cannot be initiated automatically or manually
  - During maintenance

Containment

Containment

- Contains energy released in a LOCA
- Keeps radioactive releases within limits following a LOCA
- Containment structure acts as heat sink initially

Dousing

- Absorbs the energy in the steam
- Reduce magnitude and duration of pressure pulse
- Traps soluble fission products & entrains insoluble ones

PSC and NPC

- Pressure suppression containment
  - – Each reactor in a separate building
  - – Dousing water above the reactor
  - – Part of dousing take supplies ECI
- Negative pressure containment
  - – Each reactor in a separate building or one containment structure
  - – Vacuum building with dousing tank

Normal Operation

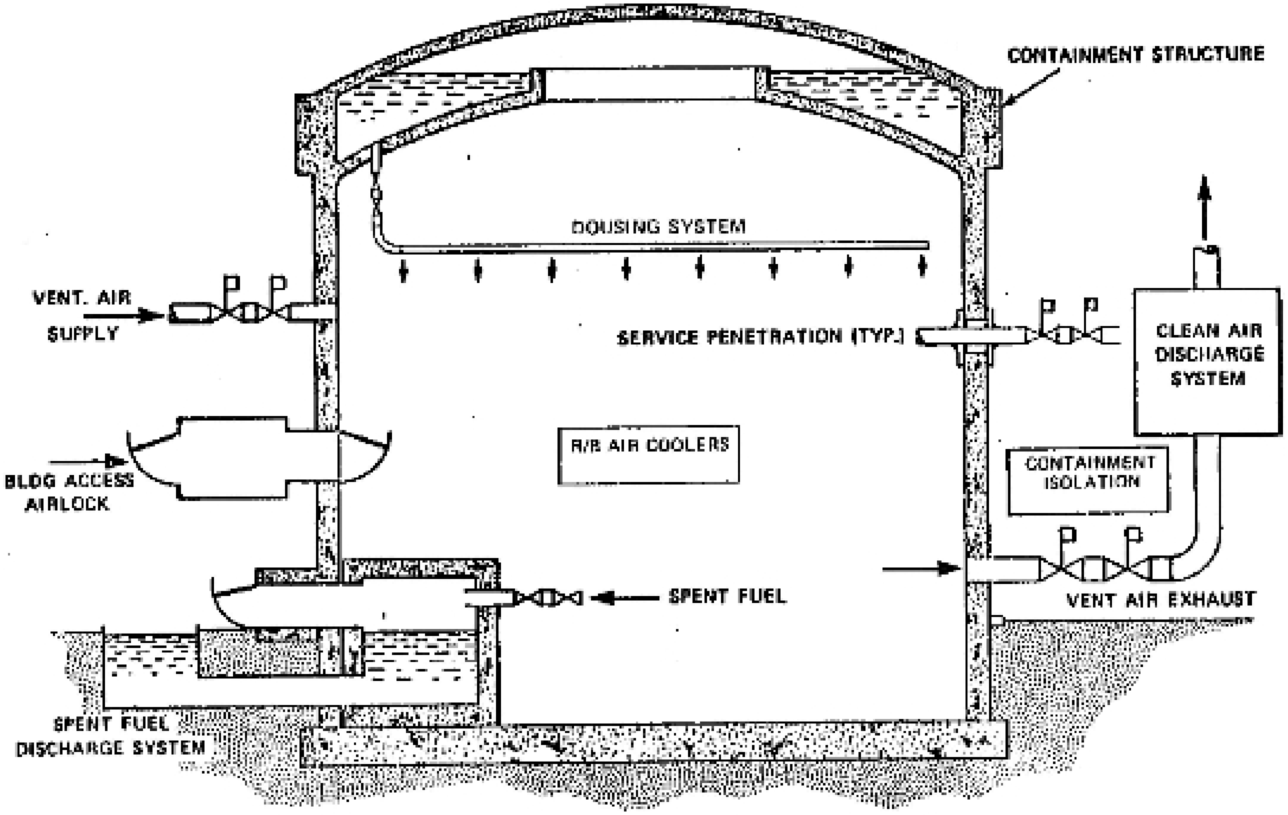
- Pressure is kept negative by ventilation
- Temperature is controlled by vault coolers
- Double isolation on lines and ducts that penetrate containment
- Airlocks for access
- Box-up or Button-up
  - High containment radioactivity, high containment pressure high exhaust or stack radioactivity, loss of stack monitoring

PSC Small LOCA

- Pressure and temperature rise is slow
- Heat removal by vault coolers increases
- For very small LOCA’s a new equilibrium may be reached.
- RB pressure > 14kPag starts dousing
- Dousing stops at 7 kPag
- May be intermittent
- As pressure falls coolers and condensation on vaults walls become major contributors again

PSC Large LOCA

- Continuous dousing at 14 kPaG
- Pressure drops quickly


CONTAINMENT STRUCTURE
DOUSING SYSTEM
VENT. AIR SUPPLY
SERVICE PENETRATION (TYP.)
CLEAN AIR DISCHARGE SYSTEM
BLDG ACCESS AIRLOCK
R/B AIR COOLERS
CONTAINMENT ISOLATION
SPENT FUEL
VENT AIR EXHAUST
SPENT FUEL DISCHARGE SYSTEM

APRV

- Auxiliary pressure relief valves
- 4, 36 inch valves
- Open first
- Modulate after LOCA to use vacuum to maintain containment pressure low

PRV

- Pressure relief valve
- Open at about 7 kPag
- Close at about half that
- 12 – 20 of these
- Very large

IPRV

- Same valve as PRV
- 3 – 4 per station
- Open at 7 kPag
- Stay open until pressure is sub-atmospheric
- Provide on-off control to maintain pressure sub atmospheric

NPC Small LOCA

- On very small LOCAs vault coolers may reach equilibrium with energy input
- On LOCAs a bit bigger APRVs may provide enough relief to prevent operation of main PRVs and IPRVs
- LOCAs larger than this will trigger all of the valves
  - but it may take time to reach this point

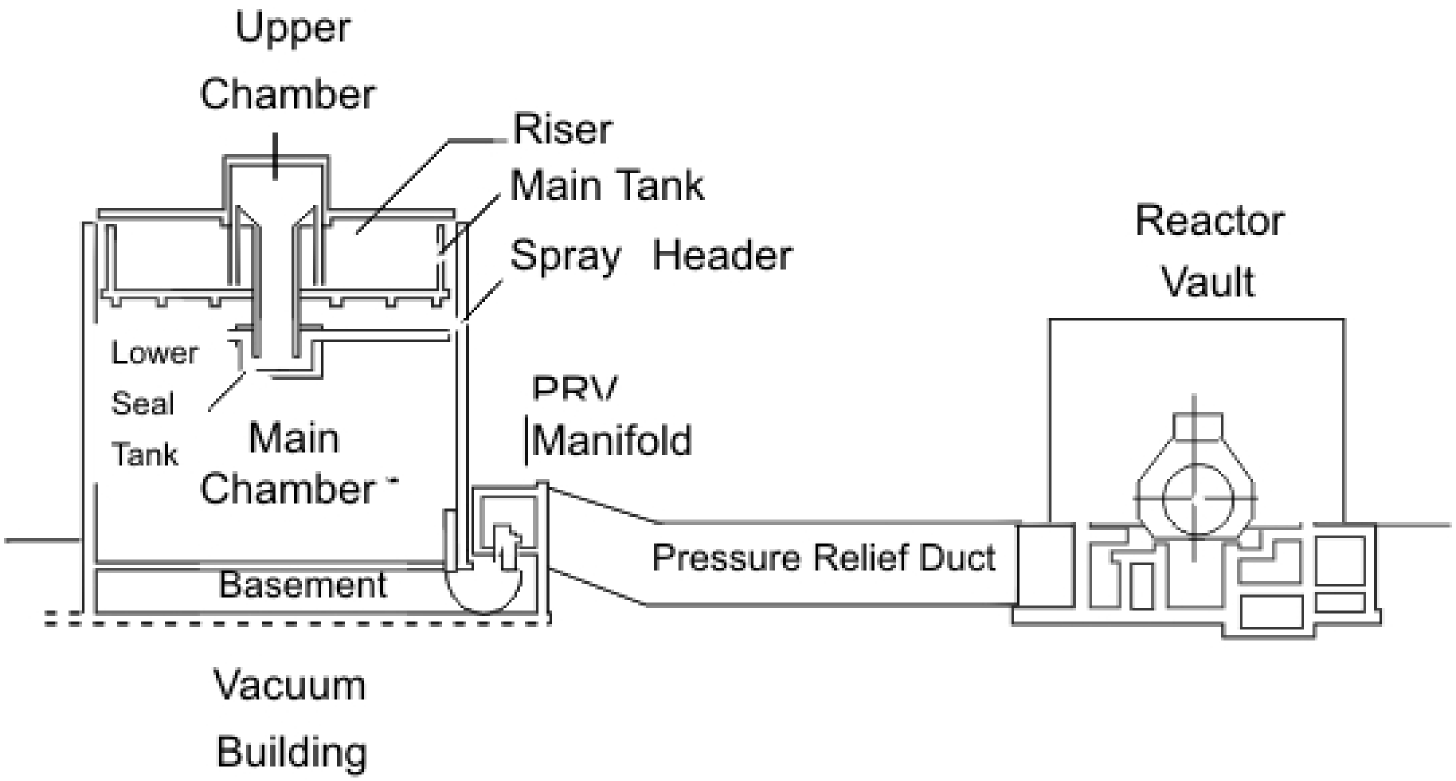
NPC Small LOCA contd.

- Dousing starts
- May be intermittent
- Containment pressure drops
  - PRVs close
  - Once pressure is stable sub-atmospheric IPRVs close
  - APRVs module to use up remaining suck in VB

Large LOCA

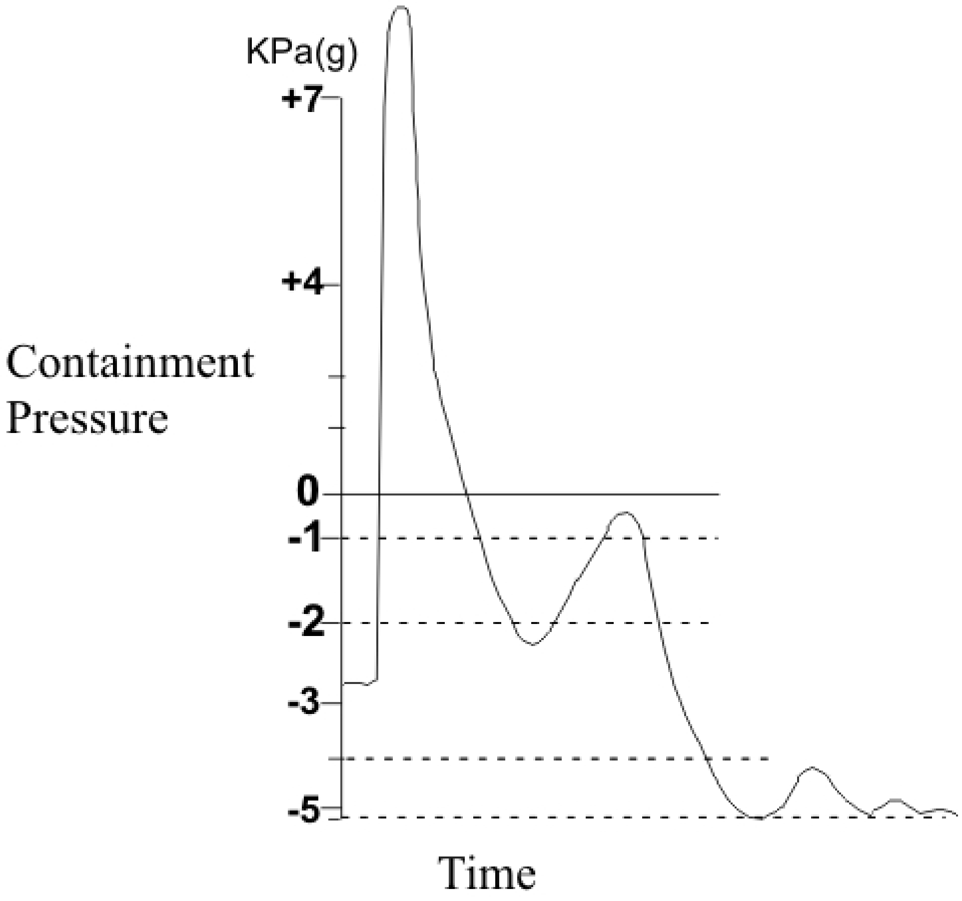
- Pressure rises quickly
- All valves open
- Dousing occurs and pressure drops
- Valves close
- APRVs maintain pressure

NPC



Upper Chamber
Riser
Main Tank
Spray Header
Reactor Vault
Lower Seal Tank
Main Chamber
PRV Manifold
Pressure Relief Duct
Basement
Vacuum Building

Containment Pressure During LOCA



Hydrogen Igniters

- Hot zirconium cause water to decompose
- If ECI fails on LOCA lots of D_2 and O_2 gas will be generated
- Hydrogen igniters (giant glow plugs) burn off the D_2 below the explosive limit
- Part of NPC
- Turn on at button up

Reactor Systems

Annulus Gas

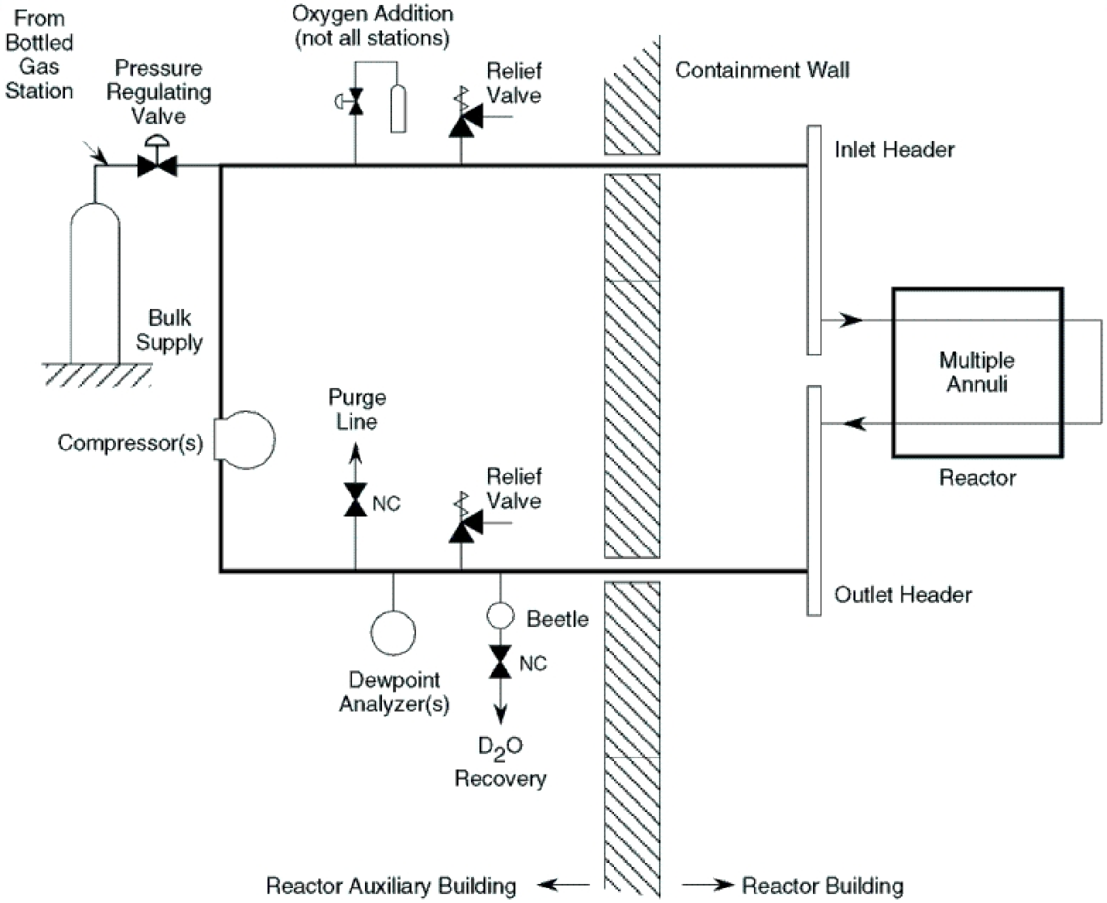
Purpose of the system

- Thermal insulation
- Leak detection
- Providing a dry atmosphere to minimize corrosion
- Provide a means to drain water from leaking pressure and calandria tubes

Gas Selection

- Low thermal conductivity
- Low tendency to promote corrosion
- Low radiation fields
- CO_2 best meets criteria
  - – Forms carbonic acid H_2CO_3 with water
    - Only mildly corrosive
  - – C-14 produced by radiative capture in C-13
    - C-13 has abundance of only 1% and a low cross section

Annulus Gas System



Important Parameters

- Pressure
  - Not controlled
  - Varies with operating conditions
  - Must be above atmosphere to prevent air inleakage
- Dew Point
  - Normally in the range of –10°C to –40°C

System Purging

- Remove accumulated moisture
  - Prevents the build up of corrosion products that can block tubing
- Remove corrosive impurities
  - Nitric acid
- Remove air
- Reduce Gamma field if Ar-41 has formed
- Lower dew point
- Maintain leak detection if compressor unavailable

Abnormal Conditions

- High gas pressure
  - Pressure tube leak
  - Thermal effects as reactor power raised
  - Pressure regulator failure
- Low gas pressure
  - System leakage
  - Loss of supply
  - System shrinkage on cool down

More Abnormal Conditions

- Annulus gas leakage
  - Reduce ability to check pressure trends
  - Radiation hazard at leak
  - C-14, tritium, entrained fission products and loose contamination
- Air in system
  - Nitric acid
  - Ar-41
  - C-14 from N-14
  - N-16 and O-19

Last abnormal condition

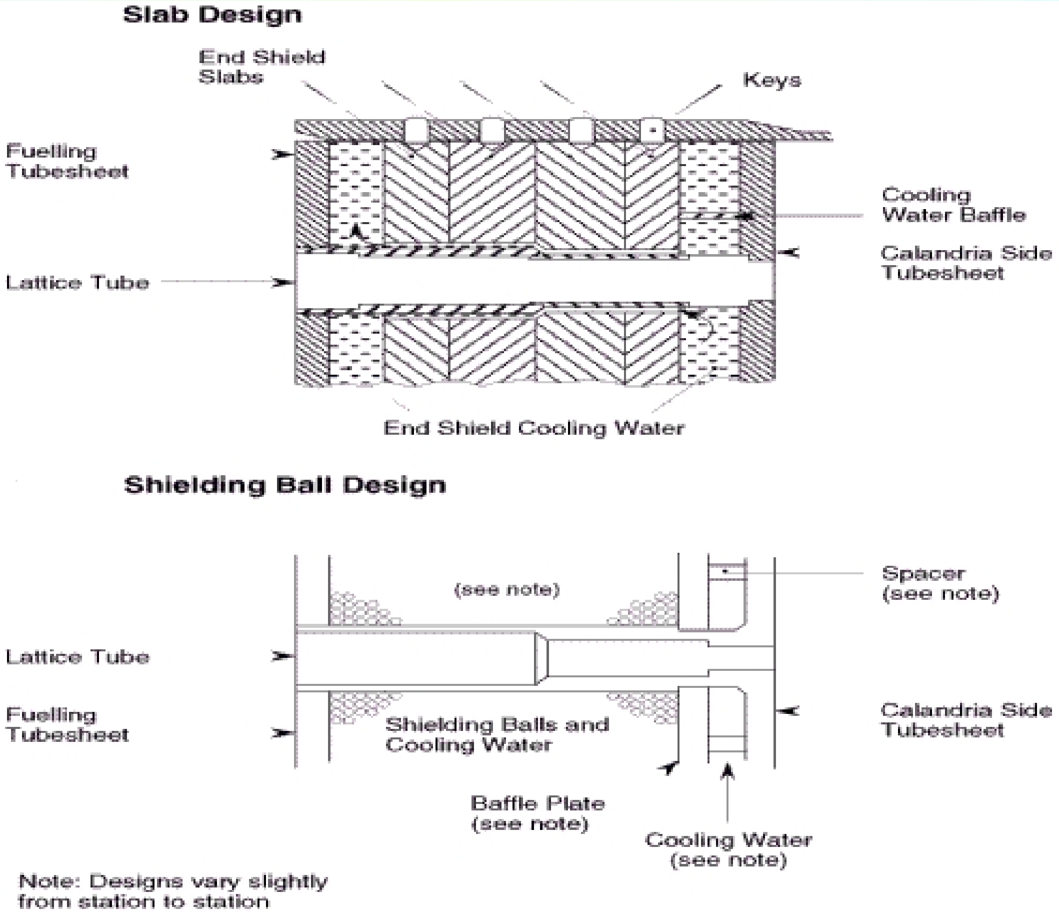
- High or Increasing Moisture Content
  - Pressure tube leak
  - Calandria tube leak
  - Air in-leakage
  - Impure gas supply

Leak Detection

- Sample from cold finger determines leak source
  - HTS, Moderator, Shield
- Stagnant mode of operation
  - No gas flow
  - Water builds up and thermally short circuits the pressure tube and calandria tube
  - HTS channel will have a lower outlet temp than the rest
- Sight glasses on annuli return lines

Shield Cooling

2 Types of End Shield

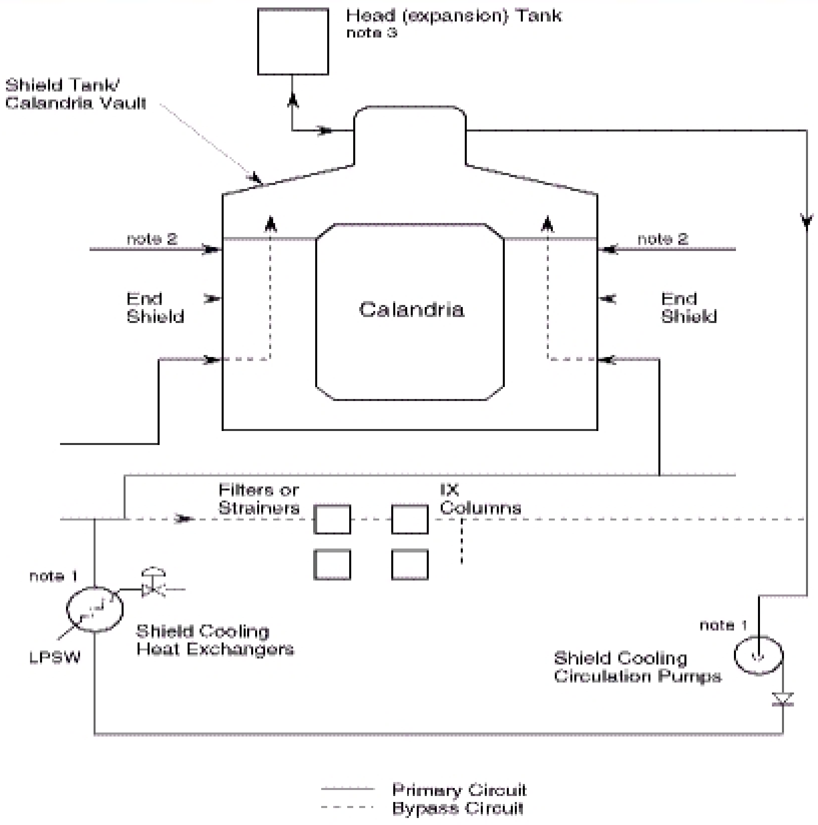


End Shield Heating

Heating

- About 1% of the total core heat
- 30% from gamma and neutrons
- 70% from conventional heating from moderator and HTS
- ΔT between moderator and end shield important
  - Thermal stress could damage welds, rolled joints, displaced slabs
- Inlet temp 60° C and outlet 65°C - 70ºC

Shield Cooling System



Note : 1. Number and capacity of components varies from station to station.
2. To baffle area or distribution pipes in tank.
3. Connected directly to pump suction in some stations.

Parameters Monitored

- Inlet/outlet temperatures
- Flow
- Shield tank head tank level
- Pressures

Loss of Shield Cooling

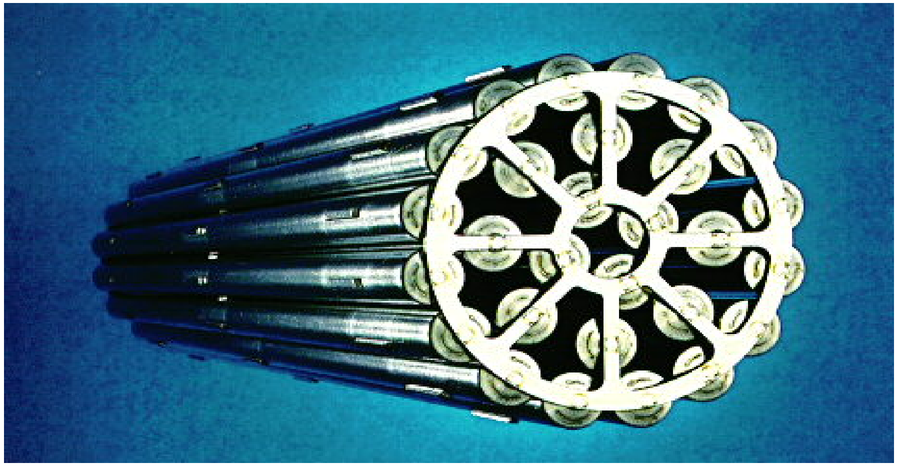
- Possible causes
  - Temperature control valves
  - Pump operation
  - Low level
  - Leaks
  - Moderator Cooling problems overloading shield cooling
- Automatic power reduction on failure of system

Requirements for Service

- Must be in service unless
  - Reactor shut down for a time period
  - Moderator cooled
  - HTS cooled
- Draining end shield
  - Huge fields will result in vault
  - Detailed thermal stress analysis
  - Corrosion control measures
  - Access to some parts of the plant restricted
  - May require CNSC approval

Thermal Shield

Fuel



Performance

- Maximized power production per bundle and channel
- Maximized energy production (burnup)
- Minimum failures
- Performance under upsets (no increased failure rate)

Units of Burnup

- Equivalent Full Power Days
  - EFPD
- Energy Extracted per Unit Mass
  - MWh/kgU
- Total Neutron Exposure
  - n/kB

100 MWh/kgU ≈ 1n.kB ≈ 115 EFPD

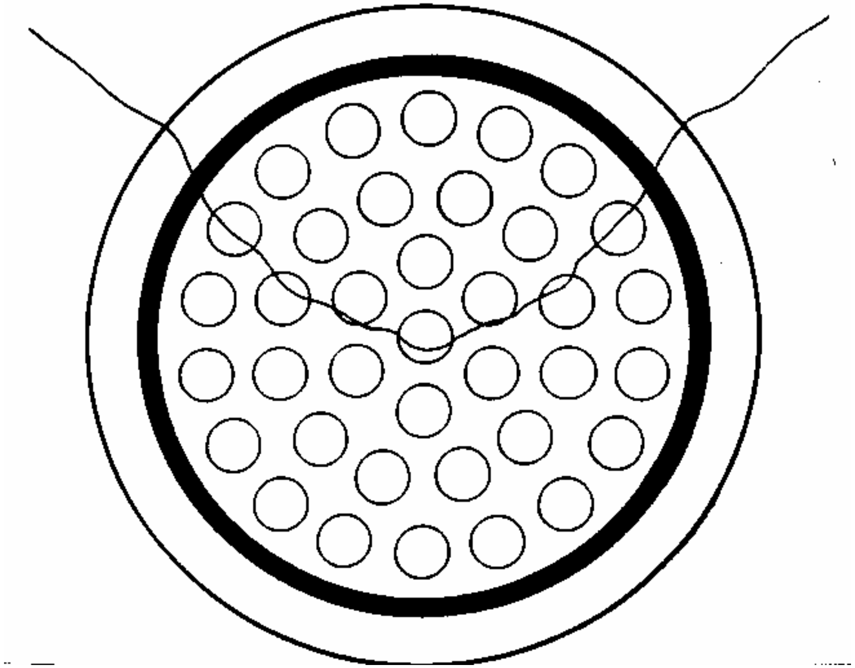
Failure Mechanisms

- Manufacturing faults
- Fretting and erosion
- Hydride cracking at endcap welds, stress corrosion cracking of sheath
- Careless handling
- Overrating
- Exposure to power ramps
- Loss of cooling

Minimizing Failures

- Inspection of new fuel
- Good housekeeping
- Maintain chemistry
- Careful handling
- Proper fuelling
- Minimize rapid power changes
- Flow and temperature monitored during fuelling
- Temp monitored all the time

Flux Shape



Reference Flux Shape

- Reference Flux Shape
  - Time averaged flux shape or continuous fuelling model flux shape
  - Day to day variations averaged out
- Deviations from the reference are called fuelling ripple

Channel Peaking Power Factor

- CPPF
  - Ratio taken for each channel of actual power to reference flux shape
  - Highest is CPPF
  - May have a factor for measurement uncertainty
- High CPPF may result in operating penalties

Fuel Overheating

- 2 Factors
  - Heat produced in fuel (power level)
  - Cooling
- Inadequate cooling will can result in dry out
  - With a normal flux shape dryout occurs in bundle near outlet, not the highest power bundles

Verification of Cooling

- Flow measurement on FINCH (at some stations)
- Temperature measurements (on non-boiling channels)
- Pressure measurements in HTS
- Thermal measurements from FINCH

Bundle Overpower

- Overpower can leads centerline melting even if there is adequate cooling
  - Center line melting will likely cause sheath failures
- Bundle power and channel power have licence limits
- Procedurally enforced
  - Cannot actually measure the bundle centerline temp
  - Because of the flux depression different elements produce different power

Dryout and Melting Protection

- NOP – neutron overpower
- ROP – regional overpower
- Protect fuel against dryout and melting
- Trip setpoints between 115% to 120% full power
- 3 arrays of detectors per shut down system
- 1 detector per array must trip for each analyzed scenario

Setpoint Determination

- Start with reference flux shape
- Analyze event
  - Loss of regulation, zone draining
  - Stop when first bundle experiences melting or dry out
- Take flux levels at detectors
- Sort through detector readings and determine setpoint for reference flux

Fueling Ripple

- Take actual thermal power
- Multiply it by CPPF
- Make NOP detectors read the product
- High CPPF may reduce margin to trip to a level power must be reduced
  - Margin to trip – difference between detector reading and trip setpoint

Abnormal Flux Shape

- Shape far from reference
  - Rod stuck in core
- Handswitch reduces NOP setpoint
- RRS has automatic power reduction on abnormal flux shapes

License Limits

- No direct measurement
- Indications
  - Bulk Power below limit
  - Flux flat (each zone close to its ideal power)
  - Reactivity devices in normal positions
    - Adjusters in, absorbers out, zones not limiting
- Calculated after an upset

Channel Power Monitoring

- Non boiling channel- power is a function of flow and ΔT
- Boiling Channel
  - FINCH takes into account increase in volumetric flow
  - Ensuring flat flux and total power within limits
  - Power occasionally reduced to check temperatures change with power
    - Ensures no flow blockages

Fuel Failure Detection and Location

- Detection – knowing it is there
- Location – knowing which channel it is in
- Removal
  - Increased risk to public from fission products in HTS
  - Increased dose in plant
  - Detection of further leaks more difficult
  - Debris could fail more bundles

Detection

- Gaseous Fission Product Monitor (GFP)
- Continuous HTS sampling
- Typically Looking for I-131, Kr-88, Xe-133, Xe-135
- Long half lives allow build up to detect small leaks

Location

- Gamma Scanning Outlet Feeders
- Delayed Neutron Detection
- Short half live isotopes
  - Can be detected at outlet feeders
  - Decay before they spread to far through the system

Gamma Scanning

- Depositing fission products
- Cling to outlet feeder
- Gamma detectors can be run past feeders
- Detectors calibrated to recognize
  - The specific gammas from depositing fission products
  - Or the increased gross gamma field from the feeder

Delayed Neutrons

- Half lives longer than photoneutrons
- Sample line from each outlet feeder is run to a neutron detector
- Feeders sampled one at a time
- Neutrons indicate channel with failed fuel

Refueling

- High burnup fuel
- Keep power distribution symmetrical
- High gain channels if overall reactivity is low
- No abnormal channel problems
- Remove defective fuel
- Avoid fuelling near recently fuelled channels
- No refueling if reactivity devices are not in the normal position
- Fuel zones with low zones

Preferred Fuelling State

- RRS in control, reactor critical
- Indication of flow blockage
- Zirconium less brittle when hot
- Need permission from management if not in preferred state

Hazards

- Fuelling machine opens pressure boundary
- Possible insertion of foreign material
- Local flux distortions

Channel Blockages

- FINCH have flow monitoring
- Outlet temp increase for non-boiling channels
- ΔP across channel (measured with fuelling machine)

Blockages

Blockage here ΔP goes down

Blockage here ΔP goes up

IFB

- Shielding against gamma
- Cooling
- Purification
- Parameters Monitored
  - Conductivity
  - Turbidity
  - Temperature
  - Level
  - Flow through purification

More IFB

- Water leaving the bay goes to active liquid waste
- Ventilation has a filtration system
- Area has gamma monitors