

Module 9

HTS HEAVY WATER**OBJECTIVES:**

After completing this module you will be able to:

- 9.1 a) Explain the two reasons why the heat transport system heavy water has a minimum isotopic limit. ⇔ Pages 2-3
- b) Explain the reason why there is an upper isotopic limit for the heat transport system heavy water. ⇔ Page 3
- 9.2 a) State the four major causes of HTS downgrading. ⇔ Page 4
- b) State the immediate and long term effects of HT system downgrading for the following conditions: ⇔ Page 4
- i) Sudden downgrading to the minimum isotopic limit specified in station Operating Policies and Principles,
- ii) Sudden downgrading to below the minimum isotopic limit specified in station Operating Policies and Principles,
- 9.3 a) Identify four potential radiological hazards of heat transport D₂O when the reactor is shut down. ⇔ Pages 5-6
- b) Identify two additional potential radiological hazards of heat transport D₂O when the reactor is operating. ⇔ Page 5
- 9.4 Explain the major purpose(s) of each of the following systems or components (number of purposes indicated in brackets):
- a) Heat transport D₂O collection system (1), ⇔ Pages 7, 8
- b) Miscellaneous D₂O collection system (1), ⇔ Page 8
- c) Vapour recovery system (4), ⇔ Pages 8-9
- d) Liquid D₂O recovery system (1). ⇔ Pages 9-10
- 9.5 State three reasons why there are limits on isotopic and purity of D₂O for return to the heat transport system. ⇔ Page 8

NOTES & REFERENCES

Pages 10-11 ⇔*Page 11* ⇔*Page 11* ⇔

9.6 For each of the following abnormal conditions, state the possible significant consequence(s) (number of consequences indicated in brackets):

- a) An abnormally high D₂O recovery/collection rate (over a period of time) (3),
- b) A pressure tube leak (1),
- c) A boiler tube leak (2).

* * *

INSTRUCTIONAL TEXT

INTRODUCTION

A primary distinguishing feature of the CANDU reactor is the use of heavy water (D₂O) both as a moderator and coolant. This section covers the HTS coolant and its requirements with respect to D₂O quality and standards. Radiological hazards of the HTS coolant will also be discussed.

ISOTOPIC LIMITS

Remember that D₂O quality is usually expressed in terms of the percentage of D₂O by mass in a given sample of D₂O and H₂O, ie. isotopic content.

For day-to-day operation of a CANDU unit, a lower limit is placed on D₂O coolant isotopic. This lower limit is set for two basic reasons: economy and safety.

1. Economy

Although the coolant plays a very minor role in terms of thermalizing fast neutrons, H₂O 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% H₂O), 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.

Obj. 9.1 a) ⇔

2. 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 channels is reduced resulting in boiling and the formation of voids. The neutrons which were previously being absorbed are now available for fission. Positive reactivity worth will increase rapidly *. Thus, the coolant isotopic must be maintained at a level such that the excess neutrons available through voiding are controllable, either by RRS or the Special Safety Systems. The normal minimum isotopic value is set by OP&P's at ~97.5%.

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

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 fuelling ahead), reactor design, moderator isotopic and shutdown system depth (to protect against in core LOCAs while shutdown and not in the GSS).

* This is discussed in more detail in the Nuclear Theory - 227 notes.

** Recall that because of the high isotopic, most of this increase is due to changes in the fast fission factor and the resonance escape probability). This is discussed in more detail in the Nuclear Theory - 227 notes.

⇔ Obj. 9.1 b)

++ This limit may be expressed as a difference between HTS and moderator isotopic.

NOTES & REFERENCES

Obj. 9.2 a) ⇔

Downgrading of HTS D₂O

The following are mechanisms which **downgrade** HTS D₂O during normal operations. All are attributable to H₂O 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) **H₂O from air in-leakage to HT D₂O 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.

Obj. 9.2 b) ⇔

Table 9.1 gives some of the expected short and long term operating effects which result from changes in D₂O isotopic.

**Table 9.1
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 ₂ O additions for makeup (typical max ~ 0.05%/month).	No observable effect, isotopic change too small.	Fuelling rate (bundles/week) reduced slightly. Higher average fuel burnup.
2 Sudden downgrading by ≤ 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 fuelling 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.

Radiological Hazards

The management and control of HTS coolant inventory must also take into account the radiological hazards which 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" on components. 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. However, these hazards are greatly increased when carrying out maintenance on system components (eg. close proximity to components or the system is opened).

⇔ Obj. 9.3 a)

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 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 radioiodine 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 the I^{131} which can result in an uptake *.

* Recall from your radiation protection training that the critical organ for Iodine uptake is the thyroid.

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

⇔ Obj. 9.3 b)

of the HTS is inaccessible when at-power (ie. 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} , as previously mentioned. Note that this will be in addition to the "conventional" hazards posed by hot, pressurized liquids.

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} .

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 personnel radiation hazard.

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 D₂O 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 D₂O recovery system is shown in Figure 9.1.

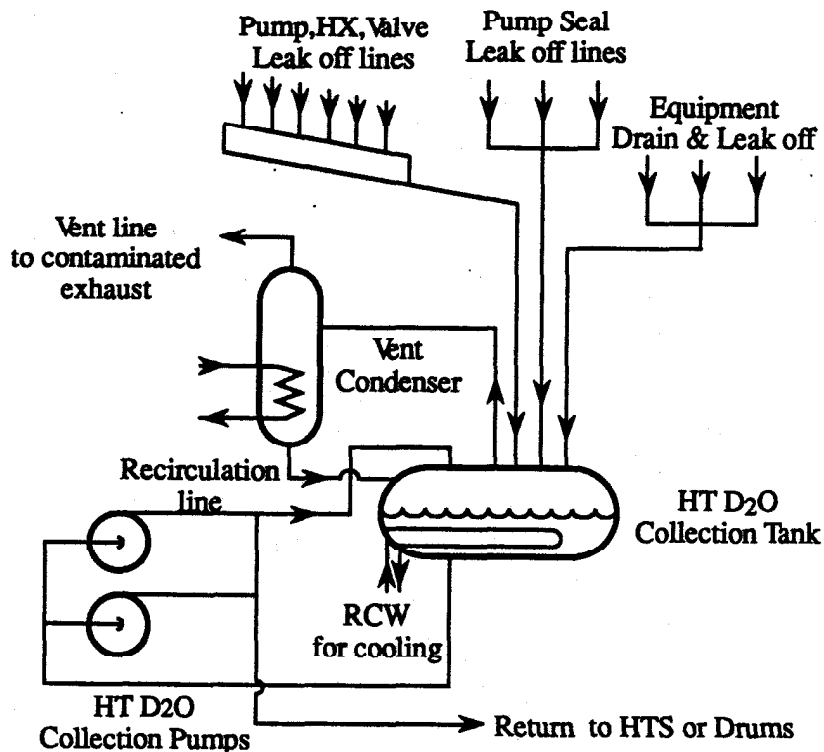


Figure 9.1
D₂O Collection System

As much of the D₂O collected 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 D₂O downgrading if tube leaks occur.

⇔ Obj. 9.4 a)

Any hot D₂O vapour is condensed in a vent condenser and the condensate returned to the collection tank. The vent condenser is also a possible source of D₂O downgrading.

The collection tank is provided with a high level alarm. When this 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. Normally, the contents meet specification and the D₂O in the tank can be returned directly to the HTS.

Obj. 9.4 a) ⇔

Leakage to this tank should not be downgraded. However, before returning it to the heat transport system, its isotopic should be checked to ensure it meets the minimum requirement (~97.5%) for the same economic and safety reasons mentioned at the beginning of the module. This D₂O must also be free of contaminants. If this D₂O is contaminated, activation of the contaminants or corrosion of the HTS may occur (this will be discussed in the Chemistry 224 course).

Obj. 9.5 ⇔

Miscellaneous D₂O Collection System

Obj. 9.4 b) ⇔

There are likely to be sources of D₂O from leakage points (throughout the reactor system) which do not meet specifications for return to the system. These collection points are routed to the miscellaneous D₂O collection system. Possible sources are the HTS collection system if D₂O collection tank contents are outside specification, the feed pump bearings and the contaminated exhaust.

For this system, the collected D₂O is fed to the upgrader or to drums.

Vapour Recovery System

D₂O leakage into the reactor vault atmosphere will form D₂O vapour, particularly when the air temperature is above normal ambient temperature. Note that reactor area vapour will not be exclusively D₂O, but will contain H₂O and other components.

Vapour will be routed to a vapour recovery system by extraction blowers. This system usually consists of desiccants which will absorb the vapours. Saturated desiccant is regenerated by heating the desiccant and releasing the now concentrated vapour to a condenser. The recovered liquid must then be returned to upgrading since it will be downgraded by the H₂O, etc, in the liquid. This system provides four advantages:

Obj. 9.4 c) ⇔

- 1) It recovers expensive D₂O.
- 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 which might serve areas such as the reactor vault, fuelling machine duct, and fueling areas.

Liquid D₂O Recovery System

The Liquid D₂O Recovery System, installed in most stations, allows the reactor to be shut down in a controlled manner in the event of a small piping rupture. The system will return sufficient D₂O 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, i.e. coolant input capability to the HTS is greater than the losses which are occurring.

Thus, this system avoids the use of ECIS with the major downgrading of coolant as a result of light water injection (and force the shutdown of the other units at multi-unit stations). This system also avoids the thermal stresses created by crash cooling and ECIS.

The basic system is shown in Figure 9.2.

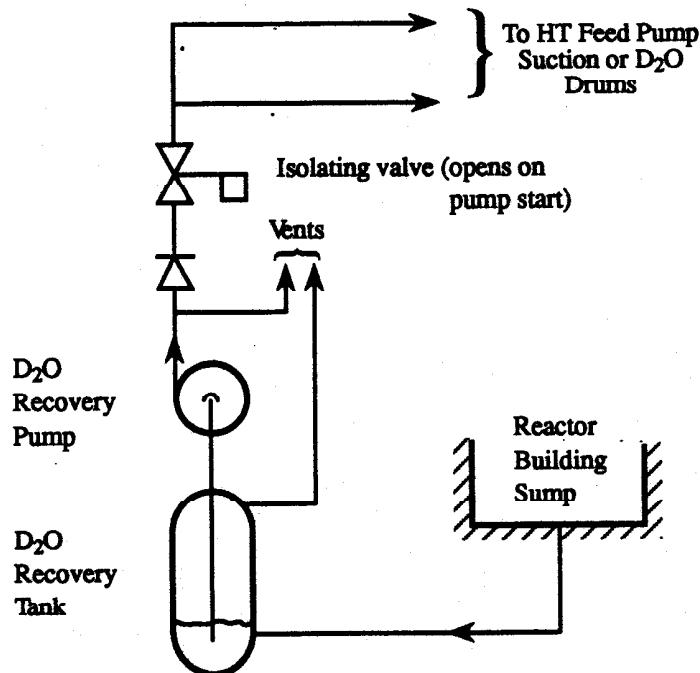


Figure 9.2
D₂O Recovery System

* This is discussed in more detail in Module 13 (Containment).

⇔ Obj. 9.4 d)

NOTES & REFERENCES

D₂O from the leak gravitates to a sump and then to a recovery tank, located at a low level in the reactor building. D₂O 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. In this latter case, any makeup D₂O required would be supplied from the unit's D₂O storage tank supplemented, if necessary, by additional supplies via the interunit tie (in multi-unit stations).

Note, that for the magnitude of leaks for which this system is designed, it is unlikely that the escaping D₂O, as it flashes to steam in the reactor building, is capable of initiating containment operation. The pressure rise in the reactor building should not exceed the containment PRV operating setpoint (for negative pressure containment systems).

SUMMARY OF THE KEY CONCEPTS

- HT D₂O collection collects leakage from leakage points in the HTS system where the collected water will likely meet specifications for return to the system. This D₂O 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 corrosion in the HTS and activation of any contaminants are minimized.
- Miscellaneous D₂O 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 D₂O 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 D₂O 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.

D₂O Leaks In The HTS

The various D₂O collection and recovery systems described can be used as a good indicator of HTS leakage and leak rates, as well as D₂O storage tank level.

Obj. 9.6 a) ⇔

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 in the form of increased replenishment and upgrading costs.

Other Leakage Indications

Other potential leak points may require additional indications other than those related to D₂O recovery rates. Two such examples are:

1) Pressure Tubes

An early indication of a pressure tube leak can be provided by constantly 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.

⇔ Obj. 9.6 b)

2) Boiler Tube Leakage

A leak in a boiler tube(s) will cause high pressure D₂O 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 to increase due to the inventory transfer from the HTS to the boiler feedwater (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:

⇔ Obj. 9.6 c)

- 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 D₂O is unrecoverable, constituting an economic penalty.**

The subject of boiler tube leaks is covered in more depth in the Turbines and Auxiliaries 234 course.

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 D₂O,

Page 13 ⇔

You can now work on the assignment questions.

ASSIGNMENT

1. The two reasons the HTS has a minimum isotopic are:
 - a) _____ . This is a concern because _____

_____.
 - b) _____ . This is a concern because _____

_____.
2. The reason that there is an upper limit on HT D₂O isotopic is _____
_____.
3. The four major causes of HT system downgrading are:
 - a) _____
_____.
 - b) _____
_____.
 - c) _____
_____.
 - d) _____
_____.

NOTES & REFERENCES

4. 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		

5. a) The four major radiological hazards associated with the HTS D₂O, when shutdown are:

- i) _____
- ii) _____
- iii) _____
- iv) _____

b) The two additional major radiological hazards associated with the HTS D₂O, when operating are:

- i) _____
- ii) _____

6. a) The purpose of the HT D₂O collection system is:

b) The purpose of the miscellaneous D₂O collection system is to

- c) The reason that these two collection systems are kept separated is _____

- 7. The purposes of the vapour recovery system are:
 - a) _____

 - b) _____

 - c) _____

- 8. The purpose of the liquid D₂O recovery system is _____

- 9. A high D₂O collection rate would have the following adverse consequences:
 - a) _____

 - b) _____

 - c) _____

- 10. The danger associated with a pressure tube leak is _____

NOTES & REFERENCES

11. The consequences associated with boiler tube leaks are:

- a) _____

- b) _____

- c) _____

12. The reason that there are limits set on HT D₂O isotopic for D₂O that is to be returned to the HTS is _____ and _____. The reason that there are limits set on HT D₂O purity for D₂O that is to be returned to the HTS is to minimize _____ and _____.

Before you move on, review the objectives and make sure that you can meet their requirements.

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