## 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 $D_2O$ when the reactor is shut down. *⇔ Pages 5-6*

b) Identify two additional potential radiological hazards of heat transport $D_2O$ 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 $D_2O$ collection system (1), *⇔ Pages 7, 8*

b) Miscellaneous $D_2O$ collection system (1), *⇔ Page 8*

c) Vapour recovery system (4), *⇔ Pages 8-9*

d) Liquid $D_2O$ recovery system (1). *⇔ Pages 9-10*

9.5 State three reasons why there are limits on isotopic and purity of $D_2O$ for return to the heat transport system. *⇔ Page 8*

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

*Pages 10-11* ⇔ a) An abnormally high $D_2O$ recovery/collection rate (over a period of time) (3),

*Page 11* ⇔ b) A pressure tube leak (1),

*Page 11* ⇔ c) A boiler tube leak (2).

* * *

# INSTRUCTIONAL TEXT

## INTRODUCTION

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.

## ISOTOPIC LIMITS

Remember that $D_2O$ quality is usually expressed in terms of the percentage of $D_2O$ by mass in a given sample of $D_2O$ and $H_2O$, ie. **isotopic content.**

*Obj. 9.1 a)* ⇔ 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.

1. **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.

## 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 absorbtion**. 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**.

* 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)***

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

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).

## Downgrading of HTS $D_2O$

*Obj. 9.2 a)* ⇔

The following are mechanisms which **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.

*Obj. 9.2 b)* ⇔

Table 9.1 gives some of the expected short and long term operating effects which result from changes in $D_2O$ 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 $D_2O$ 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.

*⇔ Obj. 9.3 a)*

The **activated corrosion products** will be distributed around the system and will tend to "**plate out**" on components. The $\gamma$ 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 $\beta$ particles. This will pose an **external $\beta$ 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).

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 $\beta$** hazards (due to a $\beta$-$\gamma$ 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.

*⇔ Obj. 9.3 b)*

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 $\gamma$ radiation** dose hazard. There is also a **neutron hazard** as a result of the decay of $N^{16}$ (which emits high energy $\gamma$, 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 (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 $\gamma$ 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 $\beta$) and, possibly $\mathbf{I^{131}}$, 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 $\gamma$, external $\beta$, tritium and $I^{131}$.
- While at power, the two major additional radiological hazards are from high energy $\gamma$ 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 $D_2O$ Collection System

*⇔ Obj. 9.4 a)*

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 $D_2O$ recovery system is shown in Figure 9.1.

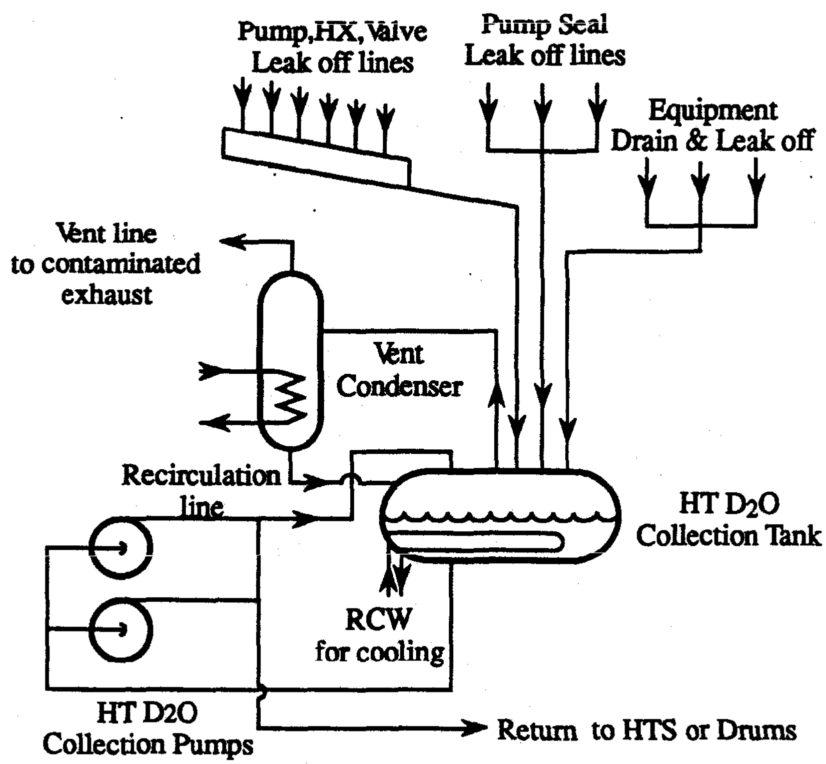


**Figure 9.1**
**D2O Collection System**

As much of the $D_2O$ 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 $D_2O$ **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 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 $D_2O$ in the tank can be returned directly to the HTS.

*Obj. 9.4 a)* ⇔

*Obj. 9.5* ⇔

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 $D_2O$ must also be free of contaminants. If this $D_2O$ is contaminated, **activation** of the contaminants or corrosion of the HTS may occur (this will be discussed in the Chemistry 224 course).

## Miscellaneous $D_2O$ Collection System

*Obj. 9.4 b)* ⇔

There are likely to be sources of $D_2O$ 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 $D_2O$ collection system. Possible sources are the HTS collection system if $D_2O$ collection tank 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.

*Obj. 9.4 c)* ⇔

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 $H_2O$, 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 *.

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

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 $D_2O$ Recovery System

⇔ *Obj. 9.4 d)*

The Liquid $D_2O$ 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 $D_2O$** 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 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.

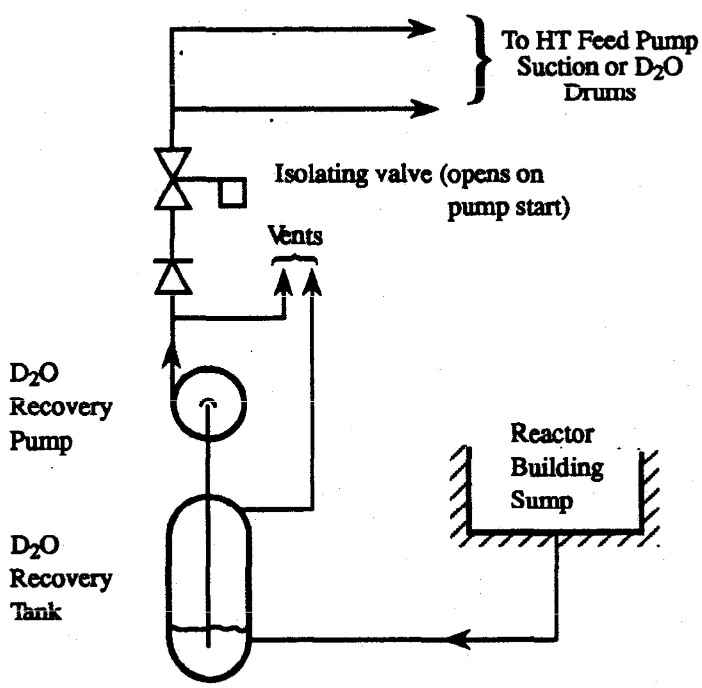


**Figure 9.2**
**$D_2O$ Recovery System**

$D_2O$ 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. In this latter case, any makeup $D_2O$ required would be supplied from the unit's $D_2O$ 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 $D_2O$, 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 $D_2O$ collection collects leakage from leakage 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 corrosion in the HTS and activation of any contaminants are 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.

## $D_2O$ Leaks In The HTS

The various $D_2O$ collection and recovery systems described can be used as a good indicator of HTS leakage and leak rates, as well as $D_2O$ 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 $D_2O$ 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 $D_2O$ 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 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 **$D_2O$ 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 $D_2O$,

*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 $D_2O$ isotopic is ____
   ______________________________
   ______________________________

3. The four major causes of HT system downgrading are:

   a) ______________________________
   ______________________________

   b) ______________________________
   ______________________________

   c) ______________________________
   ______________________________

   d) ______________________________
   ______________________________

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 $D_2O$, when shutdown are:

   i) ______________________

   ii) ______________________

   iii) ______________________

   iv) ______________________

   b) The two additional major radiological hazards associated with the HTS $D_2O$, when operating are:

   i) ______________________

   ii) ______________________

6. a) The purpose of the HT $D_2O$ collection system is:

   ______________________

   ______________________.

   b) The purpose of the miscellaneous $D_2O$ 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 $D_2O$ recovery system is ______________

______________________________.

9. A high $D_2O$ collection rate would have the following adverse consequences:

a) ______________________________

______________________________.

b) ______________________________

______________________________.

c) ______________________________

______________________________.

10. The danger associated with a pressure tube leak is ____________

______________________________

______________________________.

11. The consequences associated with boiler tube leaks are:

    a) ______________________________________________

    ______________________________________________.

    b) ______________________________________________

    ______________________________________________.

    c) ______________________________________________

    ______________________________________________.

12. The reason that there are limits set on HT $D_2O$ isotopic for $D_2O$ that is to be returned to the HTS is ____________________ and ________________. The reason that there are limits set on HT $D_2O$ purity for $D_2O$ 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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