Module 15

SHIELD COOLING SYSTEMS

OBJECTIVES:

After completing this module you will be able to:

15.1 a) State the reason why the end shield requires cooling. ⇔ *Page 2*

b) Explain the consequence of the loss of end shield cooling: ⇔ *Page 3*

c) State the approximate percentage of reactor thermal power removed by the end shield cooling system. ⇔ *Page 3*

15.2 For the end shield cooling system, list:

a) Heat sources at power (2), ⇔ *Page 3*

b) Heat transfer path, ⇔ *Pages 4-6*

c) Heat sinks (1). ⇔ *Page 6*

15.3 Explain the reason why the end shield cooling system purification loop is required. ⇔ *Pages 4-5*

15.4 a) State three parameters, other than the controlled variable (temperature), which must be monitored to ensure that end shield cooling system performance is adequate. ⇔ *Page 6*

b) Explain why each of the parameters given in a) are useful in monitoring end shield cooling system performance. ⇔ *Page 6*

15.5 State three required actions when end shield cooling has been lost. ⇔ *Pages 6-7*

15.6 a) State three conditions which must be satisfied to allow the end shield cooling system to be taken out of service. ⇔ *Page 7*

b) State the main heat source in the end shield when the reactor is shutdown and cooled down. ⇔ *Page 7*

c) Explain the reason why the end shield cooling system can be taken out of service at that time. ⇔ *Page 7*

d) Explain the three special precautions required if the end shield is to be drained. ⇔ *Page 7*

NOTES & REFERENCES

Page 8 ⇔ 15.7 a) State the reason why the biological/thermal shield requires cooling.

Page 8 ⇔ b) Explain the consequences of the loss of biological/thermal shield cooling flow.

Page 9 ⇔ c) State the approximate percentage of reactor thermal power removed by the biological shield cooling system.

* * *

INSTRUCTIONAL TEXT

INTRODUCTION

Recall from the previous levels of the Reactors, Boilers and Auxiliaries course that there are three types of shield used in CANDU reactors to protect personnel and equipment. These shields are as follows:

a) Calandria End Shields – Used to protect personnel against γ in the reactor vault during unit shutdowns only.

b) Biological Shield – Used to protect 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.

Note that in most stations that the thermal and biological shields are combined*.

* This is discussed on page 8.

This module 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.

CALANDRIA END SHIELDS

Cooling Requirements

Obj. 15.1 a) ⇔

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. This heat must be removed by the end shield cooling system.

⇔ *Obj. 15.1 b)*

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-70°C at the outlet. Recall from the moderator circulation system module (2), typical moderator inlet/outlet temperatures are 40°C/60°C).

⇔ *Obj. 15.1 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:

⇔ *Obj. 15.2 a)*

a) About 30% is due to **absorption of neutrons and γ from fission and fission products** (ie. 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. 15.1 (a) on the next page). 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).

* Recall from previous R&A courses that shutdown shielding at the face of the reactor would be inadequate without shield plugs in the channels.

The second design uses carbon steel balls for the shielding media, and is also cooled with light water (Fig 15.1 (b)). 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.

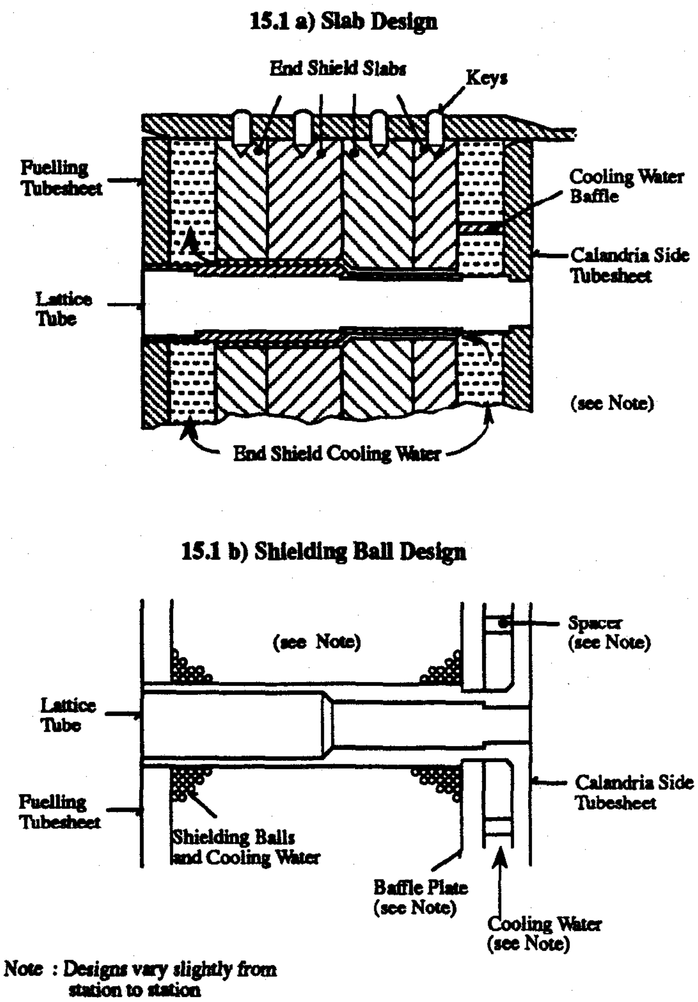


Figure 15.1 : Basic End Shield Designs

End Shield Cooling

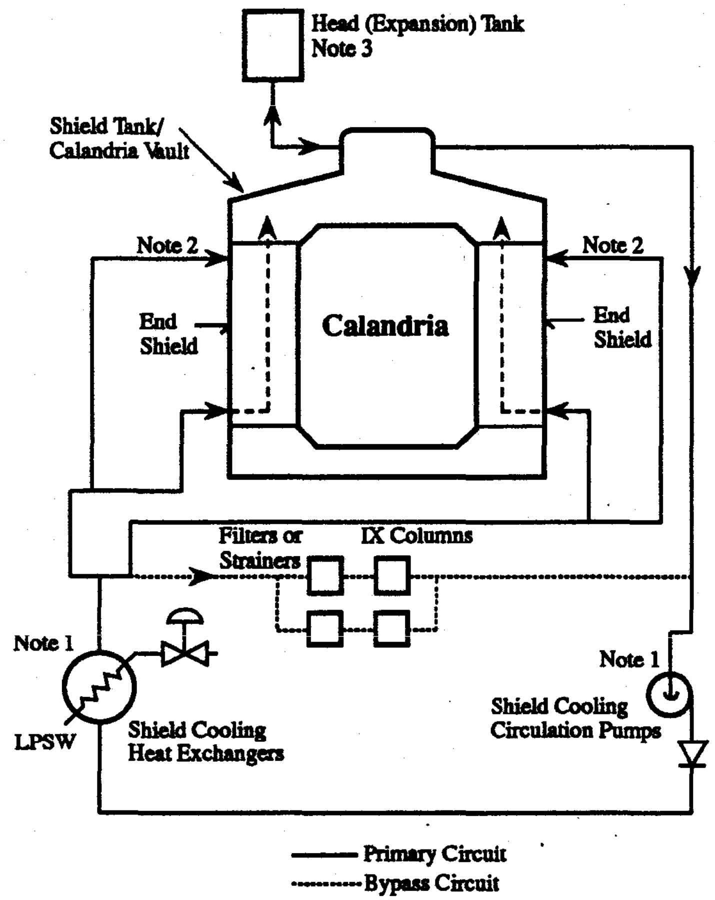
Obj. 15.2 b) ⇔

A typical shield cooling design is shown in Figure 15.2. 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).

Obj. 15.3 ⇔

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



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 15.2 : Simplified Flow Diagram for End Shield/Shield Tank Cooling Systems

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.

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 (ie. ensure proper level maintained), and to provide a positive suction head to the circulating pumps to prevent cavitation. Because of the γ and neutron fluxes, radiolysis can 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**.

Obj. 15.2 c) ⇔

Parameters, other than end shield and heat exchanger inlet/outlet temperatures, available for monitoring cooling are:

Obj. 15.4 a) & b) ⇔

- **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. This may mean there are leaks from the system,
- Gross **flow** of the coolant, to ensure coolant is flowing and will also automatically initiate additional pumping capacity as required,
- **Pressure** measurement at pump's suction, discharge, HX discharge and ΔP across the HX. These pressures will indicate flow problems, eg. break locations, flow blockages, etc.

Loss Of End Shield Cooling

Obj. 15.5 ⇔

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 (note that, 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, eg. 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.

* The rate of power reduction required will be listed in your station's operating procedures.

3) If the above actions are not successful, a **cooldown of the HTS** (or crash cooldown in some stations) will be required.

End Shield Cooling System Requirements

The end shield cooling system must be functional at all power levels of reactor operation. The shield cooling system **may be shut down** if the following conditions are met:

⇔ *Obj. 15.6 a)*

- The **reactor** has been **shut down** for a specified time period (4–24 hrs*),
- The main **moderator temperature** is less than a specified limit (~38 to 40°C*) and,
- The **HTS** is **"cold"** (≤ ~55°C*).

* Values vary from station to station.

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).

⇔ *Obj. 15.6 b)*

⇔ *Obj. 15.6 c)*

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:

⇔ *Obj. 15.6 d)*

1) Detailed stress analysis to ensure stresses due to thermal effects do not exceed design limits,

2) Measures to control corrosion are implemented and,

3) Access to reactor areas is restricted or additional shielding is provided to compensate for the loss of shielding from the water.

Note that AECB approval may also be required (depending on the station), as increased exposure risks to station personnel will exist .

THERMAL SHIELD

The thermal shields used in CANDU reactors are also of two basic designs.

Obj. 15.7 a) ⇔

The first design uses shield plates internal to the calandria. Thick stainless steel liner plates are supported inside the calandria shell. These plates are **heated by γ radiation, fast neutrons** (due to leakage) **and thermal heat** from the core. Cooling of the thermal shield is performed by the 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 which surrounds the calandria (Note: some stations use a steel tank, others use a steel lined concrete structure). This tank encloses and supports the reactor core and **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 Fig. 15.2.

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.

BIOLOGICAL SHIELDS

The design of the biological shields reflect the effectiveness of the thermal shield.

Obj. 15.7 a) ⇔

Obj. 15.7 b) ⇔

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. ⇔ *Obj. 15.7 c)*

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.

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 which 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 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.

Page 11 ⇔

You can now **work on the assignment questions.**

ASSIGNMENT

1. The end shields must be cooled because they are heated by:

   a) ____

   ____

   b) ____

   ____

2. The consequence of the loss of end shield cooling are:

   ____

   ____

   ____

   ____

   ____

3. The approximate reactor thermal power removed by the end shield cooling system is _________. The two major sources of heat at full power are:

   a) ____

   ____

   b) ____

   ____

4. The heat transfer path for the end shield cooling system is:

   ____

   ____

   ____

   ____. The

   ultimate heat sink for this system is ______________________

   ____________________________________.

5. The end shield cooling system requires a purification system because:

____

____

____

____

____

6. Three parameters (other than temperature) that are monitored to ensure adequate end shield cooling system performance are:

   a) ______________________________________,

   which is useful in monitoring performance because ________

   ____

   ____

   ____

   ____

   b) ______________________________________,

   which is useful in monitoring performance because ________

   ____

   ____

   ____

   ____

   c) ______________________________________,

   which is useful in monitoring performance because ________

   ____

   ____

   ____

   ____

7. When the end shield cooling has been lost the following major actions are required:

   a) ______________________________

   ____

   b) ______________________________

   ____

   c) ______________________________

   ____

8. The end shield cooling system can be shutdown when the following conditions are satisfied :

   a) ______________________________.

   b) ______________________________.

   c) ______________________________.

   The end shield cooling system can be taken out of service at that time because ______________________________

   ______________________________. The major

   sources of heat at this time will be ______________.

9. Three precautions required before draining the end shield are:

   a) ______________________________

   ____

   ____

   b) ______________________________

   ____

   ____

   c) ______________________________

   ____

   ____

10. a) The biological/thermal shield must be cooled because they are heated by ______________________________

____

b) If this heat is not removed, damage may occur to the ______

______________________________, leading to the following adverse consequences:

i) ______________________________

____

____

ii) ______________________________

____

____

11. The approximate reactor thermal power removed by the biological shield cooling system is ______%.

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

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Revision date: June, 1992