Module 2

MODERATOR CIRCULATION SYSTEM

OBJECTIVES:

After completing this module you will be able to:

2.1 a) For each of the following operating states, list the indicated number of major heat sources: ⇔ ***Page 2***

- i) Full power (2),
- ii) Immediately after shutdown, with the moderator in the calandria (1).

b) For the moderator circulation system, describe the: ⇔ ***Pages 2, 13***

- i) Heat transfer path,
- ii) Heat sinks,
- iii) Major equipment required for heat removal.

2.2 a) State a typical range for bulk moderator temperature under normal operating conditions. ⇔ ***Page 3***

b) Explain three possible consequences of operating outside this range. ⇔ ***Pages 3-4***

2.3 State the possible consequence of localized "hot spots" in the moderator. ⇔ ***Page 3***

2.4 Under normal operating conditions, state the required level of moderator D_2O (in general terms only) and state the indicated number of adverse consequences of operating with a: ⇔ ***Page 4***

- a) Moderator level that is too low (5), ⇔ ***Pages 4-5***
- b) Moderator level that is too high (2). ⇔ ***Page 5***

2.5 State the indicated number of adverse consequences of the following abnormal conditions:

- a) Loss of service water to the moderator HXs (6), ⇔ ***Pages 5-6***
- b) Loss of moderator circulation flow (6), ⇔ ***Pages 5-6***
- c) Moderator heat exchanger leak (2). ⇔ ***Page 6***

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INSTRUCTIONAL TEXT

INTRODUCTION

This module 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. Figure 2.1 at the end of the module can be unfolded and kept in sight for your reference.

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. (Note that in stations using boosters, this value can increase to ~7%. The rest of this discussion will ignore booster heat input to the moderator, as booster are not used for steady state operation).

Obj. 2.1 a) ⇔

Most of the heat in the moderator is generated as a result of the **fission process** (from thermalizing neutrons and absorbing fission γs). The remaining heat is produced by the absorption of γ **from fission products and activated core components.**

Immediately after **shutdown** (with HT D_2O hot), the fission component of the heat production is virtually eliminated and only about 30% of the "at power" heat load remains. Most of this remaining heat is from the absorption of γ **from fission products and activated core components.** Note also that the heat production decreases by a factor of 10 during the first day after a shutdown, mainly due to the decay of short lived fission products.

Heat removal

Heat must be removed from the moderator to prevent the following:

- Temperature increases and boiling, which have an undesirable effect on the core reactivity and cover gas D_2 concentrations.
- Elevated temperatures, since the moderator is not as effective as a heat sink to prevent a pressure tube or calandria tube failure in the event of a LOCA. In addition, large thermal stresses could occur between the end shield and the calandria if moderator temperatures are out of specified ranges.

Each of these problems will be discussed further in the module.

⇔ Obj. 2.1 b)

To prevent the problems mentioned above, the moderator must be cooled while operating and while shut down. This is accomplished by the moderator circulation system. Refer to Figure 2.1 at the end of the module for a typical moderator circulation system.

The moderator D_2O, which is pumped through the moderator heat exchangers, is cooled by service water. Eventually, the heat ends up in the lake (river or sea, depending on the station).

The flow is distributed to various locations in the calandria to minimize the occurrences of local "hot spots", and to ensure all components are cooled.

During normal operation, full flow is maintained through the calandria to keep components cool.

During shutdown periods (and also depending on the amount of time since shutdown), a reduced circulation flow can be used (ie. fewer pumps/heat exchangers or the use of smaller auxiliary moderator circulation pumps) to remove the heat. In stations where the moderator is dumped, cooling to the core components is maintained by calandria sprays, which cool the critical core components (calandria tubes, reactivity mechanisms, dump ports, supports, etc.).

Moderator temperature control

⇔ Obj. 2.2 a)

⇔ Obj. 2.2 b)

The moderator temperature is controlled by varying the service water flow through the moderator heat exchangers. The **temperature** at the moderator inlet is controlled to ~40°C. With this inlet temperature, and while operating under normal conditions, the outlet temperature is normally ~60°C. Temperatures outside this operating range must be prevented for the **following reasons:**

a) Temperature increases must be prevented.

- 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 voids decrease core lattice pitch effectiveness (eg. no moderation will occur in the steam bubbles). Since our reactors are over-moderated, this can cause the **core reactivity to increase** (until the boiling becomes excessive, which will then cause under-moderation).

* This is discussed in the Nuclear Theory course (227).

NOTES & REFERENCES

Obj. 2.3 ⇔

- 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.

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.

The maximum temperature also depends on the pressure in the moderator, ie. conditions must be maintained below saturation. Pressure in the moderator is maintained by the cover gas system at approximately 10 to 25 kPa(g) *. Also, we must realize that no heat removal path is perfect, and local hot spots may exist within the calandria. This means that temperatures must be maintained below ~100°C, with a sufficient margin to boiling to accommodate the local "hot spots". (Note, if a higher temperature was desired for the moderator, the calandria would be required to be a large pressure vessel -leading to increased costs).

* At the upper free surface.

b) 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.

c) The moderator may have to act as a reactor **heat sink** under severe accident conditions (severe LOCA). In this situation, fuel channel voiding will cause fuel channel overheating and sagging. And, if fuel cooling is not restored, eventually the fuel channels will contact the calandria tubes. When contact occurs, the heat is conducted through the fuel channel and calandria tube to the moderator D_2O. This will maintain pressure tube integrity. Hence, as the temperature of the moderator increases, its capability as a heat sink is reduced.

Moderator level

Obj. 2.4 ⇔

The major function of the moderator is to thermalize fast neutrons. The function of the moderator circulating system is to cool the moderator and calandria components. Considering these functions, the moderator D_2O level must be **sufficient to minimize neutron leakage from the core and cool the core components.**

Obj. 2.4 a) ⇔

A **low moderator level** can cause the following problems:

a) **Overheating** of the calandria components if they lose their cooling from the moderator D_2O. This is especially true for the calandria tubes.

b) Removal of **reactivity**, especially if calandria tubes are no longer submerged in the moderator D_2O. But, even if all the calandria tubes are still covered, a loss of reactivity can still occur because a lower level results in increased neutron leakage (ie. the moderator performance as a neutron reflector is reduced).

c) **Severe flux tilts** if power is maintained at reduced levels (other reactivity devices will operate to maintain power)

d) The rate of **deuterium evolution** from the top of the moderator D_2O will increase as surface area increases. This will lead to a shutdown if the deuterium concentration in the moderator cover gas reaches the shutdown limit. The normal operating level is kept above the calandria (as illustrated in Figure 2.1) to minimize the D_2O area exposed to the cover gas (ie. due to the shape of the calandria, as level decreases near the top, D_2O surface area increases).

e) In some stations, **ion chamber response** will be affected as the detectors at the top of the calandria become exposed to the cover gas (ie. lose the shielding effect of the moderator D_2O).

A **high moderator level** can cause the following problems: ⇔ *Obj. 2.4 b)*

a) **Insufficient space** in the calandria to accommodate the poison injected when SDS2 fires. This could result in the bursting of the calandria rupture discs. Also, insufficient room could exist for thermal expansion of the moderator as heat input increases during startup.

b) Possible **flooding** of the **SDS2 helium injection header**. (Note that as level in the moderator increases, so does the level in the SDS2 injection tanks.) If the level rises sufficiently, the D_2O/poison mixture will rise into the He injection piping. As the poison tank level increases, the moderator D_2O/poison interface moves away from the calandria. This would result in a delay of poison injection when the Shutdown System initiates. Water in the He injection piping can also cause severe water hammer if SDS2 fires.

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 following: ⇔ *Obj. 2.5 a), b)*

a) The increase in moderator temperature will cause an increase in reactivity due to the positive moderator temperature coefficient (the moderator temperature is positive for equilibrium fuel, but negative for fresh fuel)*. If operation continues, localized boiling will start, causing further **reactivity increases and operational instability**.

* This is discussed in the Nuclear Theory course (227).

b) Equipment will also overheat, resulting in **damage due to thermal stressing.**

c) Also in this case, the moderator **may not be an effective heat sink** (as explained earlier in this module).

d) As boiling occurs, **pressure could increase in the calandria,** causing a burst rupture disc. The required actions would be to shut down the reactor and to cool down the HTS to limit heat input to the moderator. Containment should also be buttoned-up (boxed-up) to ensure that tritium releases to the environment are controlled (in case a rupture disc bursts).

e) As the moderator temperature increases, the D_2O will swell. The **level control** response of the moderator system may not be quick enough to prevent SDS2 injection header flooding.

f) As the moderator temperature increases, **D_2** will come out of solution from the moderator *. This can lead to an **explosive mixture** of D_2 and O_2 in the cover gas.

* This is discussed in more detail in Module 3.

Moderator Heat Exchanger Leak

Obj. 2.5 c) ⇔

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 our target of 1% of the 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.

SUMMARY OF THE 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). The major heat source in the moderator while shut down is from fission product and activated core component γ absorption.
- The optimum temperature range for the moderator D_2O is ~40° C at the inlet and ~60°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 an effective 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 accomodate 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 represent an economic penalty and a radiological emission concern.

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

⇔ ***Page 9***

ASSIGNMENT

1. The two major moderator heat sources at power are:

   a) ____

   ____

   b) ____

   ____

2. The major moderator heat source with the reactor shut down is

   ____

   ____

3. For the moderator circulation system, describe the heat transfer path and the major components required to remove the heat produced

   ____

   ____

   ____

   ____. The ultimate heat sink for the moderator is______________________

   ____

4. The normal moderator D_2O temperature range is ______________. Low moderator temperature can cause thermal stresses between

   ____.

5. High moderator temperatures can cause the following three effects:

   a) ____

   ____

   ____

   ____

   ____

   ____.

b) ____

____

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____.

c) ____

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____.

6. Localized hot spots in the moderator will cause ________________
This will lead to ______________________________.

7. The normal required level of the moderator (in general terms) is

____

____

8. A low moderator level can cause:

a) ____

____

b) ____

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c) ____

____

d) ____

____

e) ____

____

9. A high moderator level can cause:

a)

b)

10. Loss of cooling to the moderator D_2O can be caused by:

a)

b)

11. The six consequences of a moderator loss of heat sink are:

a)

b)

c)

d)

e)

f)

12. A moderator heat exchanger leak can cause the following adverse consequences:

    a) ______________________________

    ____

    ____

    b) ______________________________

    ____

    ____

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

Prepared by: N. Ritter, WNTD
Revised by: P. Bird, WNTD
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