

## 12 Moderator And Moderator System

### 12.1 Introduction

Nuclear fuel produces heat by fission. In the fission process, fissile atoms split after absorbing slow neutrons. This releases fast neutrons and generates heat. Fast neutrons are not very good at causing fissions. The moderator slows the fast neutrons so they will cause more fissions. It must do this without absorbing too many, or the chain reaction will stop.

Most neutrons, on collision with a heavy water molecule, hit and bounce. These collisions transfer energy from fast moving neutrons to the heavy water. This slows the neutrons and heats the heavy water. The moderator system cools the heavy water by circulating it through heat exchangers. The last section of this module describes the circulation system.

Moderator water contains mostly heavy water with a very small amount of ordinary water. Fewer than 2% of the fission neutrons are absorbed in the moderator. The small H<sub>2</sub>O impurity captures about half of these. The next section explains the importance of keeping the light water impurity small, and describes how this is done.

Occasionally a deuterium nucleus in D<sub>2</sub>O captures a neutron and becomes tritium. Tritium is a radiation hazard. Neutrons may also interact with the oxygen nuclei, producing other radiation hazards. This module discusses these hazards.

The water molecules are broken into fragments by the energetic collisions. The next module describes the effects of this on moderator operation.

### 12.2 D<sub>2</sub>O Isotopic

A sample of moderator water is typically about 99.8% by weight D<sub>2</sub>O and 0.2% H<sub>2</sub>O. We say it has an isotopic of 99.8%. The exact definition is:

$$\text{Sample D}_2\text{O Isotopic} = \frac{\text{Mass of D}_2\text{O In Sample}}{\text{Mass D}_2\text{O} + \text{Mass H}_2\text{O In Sample}} \times 100\%$$

The number of neutrons absorbed is sensitive to changes in isotopic. An impurity of less than 0.2% light water will absorb half the neutrons absorbed by the moderator.

If the isotopic drops a few tenths of one per cent, extra fuel can offset the neutron losses. This increases fuel costs. A decrease in isotopic from 99.8% to 99.7% increases fuel costs between a half million dollars and one million dollars a year. Similarly, upgrading the moderator by 0.1% saves this amount of money.

If the isotopic drops below 99.5%, the reactor may stop running. A D<sub>2</sub>O upgrader at the station upgrades low isotopic heavy water to 99.9% or higher. The isotopic of the upgrader product depends on the amount and isotopic of the heavy water it must process, and the time available.

Careless handling of heavy water is expensive. Your job may involve transferring heavy water, by adjusting valves or emptying drums. If so, always think twice. A wrong transfer can mix low and high isotopic. The result could be extra upgrading and fuel costs, or, expensive heavy water could go down the drain. Even worse, you might cause a power outage.

### **12.3 Summary Of The Key Ideas**

- The heavy water isotopic is the mass % of D<sub>2</sub>O. Moderator isotopic is usually near 99.8%. The other 0.2% is ordinary water.
- The isotopic requirement for the coolant is less rigid. The coolant is exposed to far fewer thermal neutron collisions, so its isotopic has less effect on neutron absorption.
- A small decrease in isotopic increases the fuel cost. A large drop in the isotopic causes the reactor to shut down.
- A D<sub>2</sub>O upgrader maintains high isotopic. Mistakes that downgrade heavy water are costly.

### **12.4 Radiation Hazards**

Significant numbers of neutrons are present in the core when reactor power is a few percent of full power or higher. These neutrons interact with D<sub>2</sub>O to produce radioactive nitrogen-16, oxygen-19 and tritium.

Tritium (H-3) forms when deuterium absorbs a neutron. Neutrons interact with naturally occurring oxygen isotopes to produce N-16 and O-19. These isotopes affect work you do in the plant.

N-16 and O-19 emit very high energy gamma rays along with energetic beta particles. The beta particles do not penetrate pipe walls,

but the penetrating gamma rays are a hazard around equipment containing these isotopes.

N-16 and O-19 have short half-lives. These isotopes decay to harmless levels a few minutes after a reactor shut down, allowing access to the equipment. Radiation from these isotopes returns to unsafe levels just seconds after restarting.

Systems that handle water circulating from the reactor core can be approached only with the reactor shutdown. Very heavy shielding around this equipment may allow work on nearby equipment with the reactor running. D<sub>2</sub>O that leaks from a reactor at power exposes anyone nearby to beta and gamma radiation and tritium.

A few systems require attention when the reactor is at power. When required, a delay tank between the core and the equipment delays the flow of D<sub>2</sub>O. This gives time for N-16 and O-19 to decay before they reach accessible areas.

The naturally occurring oxygen isotopes are O-16 (99.76%), O-18 (0.2%) and O-17 (0.04%). O-19 comes from neutron absorption in an O-18 nucleus. N-16 comes from an (n, p) reaction with O-16. (Some N-17 is produced by an (n, p) reaction with O-17 and some C-14 is produced by an (n, p) reaction with O-17).

O-19 has a half-life of about 27 seconds. N-16 has a half-life of 7.1 seconds.

Tritium (H-3) has a half-life of 12.3 years. Its concentration builds gradually in moderator and heat transport D<sub>2</sub>O. It hardly decreases on a shut down.

Tritium emits a low energy beta particle and no gamma ray. Normal radiation instruments cannot detect tritium. A person with Radiation Protection Training (RPT) qualifications can check most workplace radiation hazards

The low energy beta particle from tritium is not an external radiation hazard. Tritium, nevertheless, is a serious internal radiation hazard. Tritiated water vapour enters the body through the lungs and through the skin. It then disperses to all parts of the body, just as normal water does. Body tissues and organs have no dead layer of skin to protect them.

Moderator water has the highest tritium concentration in the plant. Tritium escapes when the system is open for maintenance. Little

escapes otherwise because the calandria is not pressurized, and there are few leakage points. In older stations, a combination of high tritium concentration and small leaks can, nevertheless, produce a significant tritium hazard from the moderator system.

Tritium also builds up in the heat transport system heavy water. This water is hot and pressurized, and the system has many more possible leak points. During normal operation the coolant contributes more tritium to the station than does the moderator water.

Neutrons produce less tritium in the coolant than in the moderator because:

- a) Moderator water spends most of its time exposed to neutrons in the reactor core. The heat transport heavy water spends less than 5% of its time passing through the core.
- b) The concentration of thermal neutrons is higher in the moderator than in the coolant.

Station staff wear positive pressure plastic suits with supplied breathing air to work in atmospheres containing tritium. These suits are required even when a small leak or spill of tritiated  $D_2O$  occurs. Full protection is needed any time maintenance crews open a  $D_2O$  system.

In the future it will be possible to control the tritium problem. In 1990, a tritium removal facility started operating at the Darlington site. It is designed to remove 99.5% of the tritium in the heavy water it processes. This water with a very low tritium concentration is put back into an operating reactor moderator diluting the tritium in the moderator. The moderator in an operating reactor typically contains 14 ci/l of tritium.

### **12.5 Summary Of The Key Ideas**

- Neutron interactions in the moderator produce the radioactive isotopes H-3 (tritium), N-16 and O-19.
- The radiation hazard from tritium is independent of reactor power. The tritium beta particles do internal biological damage.
- N-16 and O-19 produce intense gamma radiation, limiting access to equipment in a running reactor. They disappear after a shutdown.

- Heavy water may leak in normal operation or when a system is open for maintenance. This produces dangerous levels of tritium in the atmosphere. Protective equipment allows work where there is tritium.
- Moderator D<sub>2</sub>O has the highest tritium content in the plant. No other system exposes the D<sub>2</sub>O to so many neutrons. Bombardment of the moderator is continuous and the thermal neutron concentration is higher there than anywhere else.

## 12.6 The Main Moderator System

The main moderator system, sometimes called the moderator circulating system, has one main purpose. It maintains a constant moderator temperature in the calandria. The moderator temperature is, typically, 60°C to 80°C.

The circulation system also supplies D<sub>2</sub>O flow to several auxiliary systems.

If the tritium concentration is very low it may be possible to do short jobs wearing an appropriate air filter, or an air supply but no plastic suit.

### 12.6.1 Moderator Heat Sources

Previously it was pointed out that the overall efficiency of a plant is about 30%. The steam condensers reject about 65% of the heat produced and the moderator heat exchangers discard about 5%. Even 5% of the total is a large amount of energy. If moderator heat removal stops, the moderator in a reactor at full power starts boiling in just a few minutes. Even a shut down reactor causes significant moderator heating.

At full reactor power, the sources of moderator heat are:

- a) The prompt radiation from fission (neutrons and gamma rays) produce 70% to 80% of the heat in the moderator. The neutrons typically contribute more than half of this.

The moderator absorbs energy slowing the fast neutrons. The prompt gamma rays that accompany fission deposit energy in the moderator water and in the shielding. They also deposit energy in structures, (for example, the calandria tubes) which the moderator cools.

This heat source disappears when the fission process stops.

b) Gamma rays from fission product decay and from decay of activation products in reactor components produce 15% to 25% of the heat in the moderator. This heat decreases slowly after a reactor shut down.

c) Conventional heating (conduction, convection, thermal radiation and friction) accounts for about 3% to 5% of moderator heating.

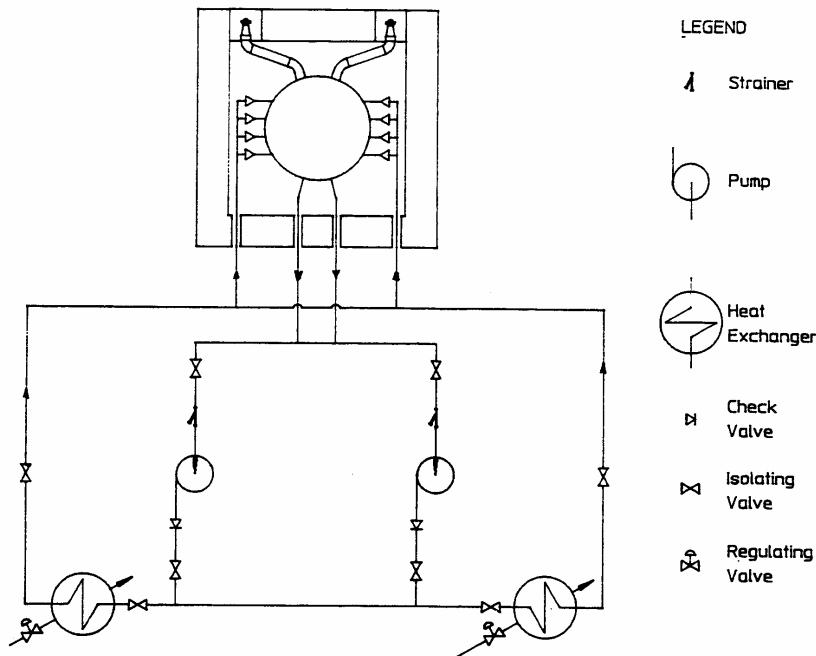
The annulus gas does not insulate the hot pressure tube perfectly.

Conduction and convection transfer some heat through the annulus gas and heat radiation transfers some heat across it. The moderator pumps, when running, also produce heat by fluid friction.

The operator can reduce the conventional heating of the moderator after a reactor shut down by cooling the heat transport system.

Each neutron loses about 2 MeV of energy and each fission creates, on average, 2.5 neutrons. This works out to about 2.5% of the heat produced by one fission.

Heat may be conducted through the calandria tube sheet in or out of the moderator, depending on the temperature difference between the moderator and the end shield.



**Figure 12.1**  
**Main Moderator Circulating System (Typical)**

Safe plant operation requires moderator heat removal to be available always. A review of the heat sources shows there is a lot of heat, even with the reactor shut down. All plants provide some sort of backup cooling arrangement to remove heat if the normal equipment is not available.

The backup cooling equipment must be large enough to handle the reduced heat output after a shutdown. In some plants there is a smaller auxiliary system with pumps, piping and heat exchangers. Other plants provide standby pumps or small, backup motors for the main pumps.

### 12.7 The Moderator Circulation System

Figure 12.1 shows the arrangement of the main moderator circulation system.

Moderator pumps take suction from outlets at the bottom of the calandria. They return cooled  $D_2O$  through inlets on the sides of the calandria. Heat exchangers downstream from the pumps transfer heat to the service water system, a light water cooling system.

The flow of service water through the heat exchangers controls temperature. When the moderator outlet temperature is high, the

moderator temperature control valves in the service water piping open further. This increases the flow of cooling water, removing more heat. As temperature drops, the valves close in, reducing heat removal.

Two calandria outlets feed the pumps through a common pipe, the suction header. A balance header connects the pump discharge outlets. These connections provide common suction and discharge conditions for each pump, helping balance the flow through the heat exchangers.

The piping arrangement also allows heat removal to continue after isolation of a single pump or heat exchanger for maintenance. Notice the check valves (to prevent reverse flow through a failed pump) and the isolation valves (for maintenance).

Heat exchangers and pumps are equipped with drain valves to allow maintenance. In some plants the service water temperature can drop below 4°C, the freezing point of heavy water. Damage can occur to a heat exchanger when it is isolated for maintenance if the cold cooling water is not drained.

Some stations have two banks of smaller pumps.

## **12.8 Summary of Key Ideas**

- The main moderator system provides moderator temperature control. It also provides flow through moderator auxiliary circuits.
- Heat enters the moderator from three sources: prompt and delayed nuclear radiation and conventional heat transfer. Moderator heat is typically 5% or so of the gross heat produced by the reactor.
- Prompt radiation from fission produces about 75% of moderator heating. Over half of this results from the moderator doing its job: slowing down fast neutrons. Absorption of prompt gamma radiation accounts for the rest.
- Heating by decay gamma radiation comes mostly from decay of fission products in the fuel.
- Conventional heating of the moderator is less than 5% of the total moderator heat. It comes mainly from the hot pressure tubes.



- The main moderator circulating system removes heat from the moderator. Pumps draw hot D<sub>2</sub>O from the bottom of the calandria and return it through heat exchangers that remove heat.
- Because there is a lot of heat produced in the moderator, even with the reactor shut down, heat removal from the moderator must continue at all times. Auxiliary equipment is available for heat removal if the normal equipment is unavailable.
- Temperature control valves vary service water flow through the heat exchangers to control moderator temperature. This adjusts cooling flow to match heat production.

### 12.9 Assignment

1. Define isotopic, and give a typical value for moderator isotopic.
2. What is the problem if the moderator isotopic decreases by:
  - a) 0.1%?
  - b) 0.5%?
3. What is done with low isotopic heavy water?
4. List the three main radiation hazards associated with the moderator system. Describe how each affects maintenance work.
5. Explain the following statements:
  - a) Tritium production is higher in the moderator than in the coolant.
  - b) Tritium from the heat transport coolant contributes more to the station staff radiation dose than tritium from the moderator.
6. What purpose does the moderator circulation system provide in addition to removing heat from the moderator water?
7. What are the main moderator heat sources in a shut down reactor?
8.
  - a) What is the biggest moderator heat source if the reactor is at 50% full power?
  - c) What happens to the moderator temperature control valve if reactor power increases?
9. Why is it necessary to have backup cooling for the main moderator system?
10. Label the two main pumps, the two heat exchangers and both temperature control valves in Figure 12.1.